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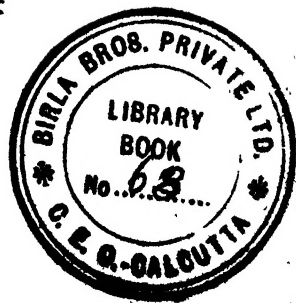
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METALS HANDBOOK



1939 EDITION



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Presentation and Appreciation

A.S.M. Metals Handbook contains approximately five hundred articles on metals and their alloys. These articles were prepared by authors or by committees under the direction and supervision of the Metals Handbook Committee. The men who have prepared Metals Handbook are all specialists and authorities in their particular field. This Handbook has been made possible by the co-operation of a large number of the members of the American Society for Metals. Approximately 2500 members have contributed in some way in the compilation of this Handbook.

Our thanks and appreciation are extended to the authors, to members of all the committees, to the reviewers of articles and to the many firms who have so generously permitted their men to devote hours of valuable time to the preparation of this volume, who by their whole-hearted co-operation have made possible this edition of Metals Handbook.

A considerable portion of Metals Handbook deals with non-ferrous metals and was prepared under the direction of the Non-ferrous Data Sheet Committee of the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers. We wish to take this opportunity to record the sincere appreciation of the membership of the American Society for Metals for the production of this very valuable portion of Metals Handbook.

The volume is now presented to the members of the American Society for Metals with the hope and belief that it will be of great service not only to the members but to the entire metal industry.

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PREFACE

*I*N THE preparation of *Metals Handbook*, the endeavor has been made to prepare a comprehensive volume of metallurgical subjects pertaining to the manufacture, treatment, and application of metals so that the metallurgist, engineer, student, and all those interested in metals will have readily available an authoritative reference book covering the field of metals and their alloys. In compiling the material for this edition, the committees in charge of the work have selected those subjects having the most extensive interest. It is the aim to make *Metals Handbook* a complete book of reference on the subject of metals and this edition indicates that the attempt towards this end is becoming successful. Additional articles will be added and it will, therefore, eventually include the more specialized subjects dealing with metals.

The same plan for the selection of subjects and for the arrangement and compilation of the subjects in the *Handbook* has been followed that was used in previous editions. This plan, formulated by R. S. Archer, consists of arranging the articles under several major headings as shown in the Table of Contents. *Metals Handbook Committee* has found this system very helpful in assigning subjects to authors and subcommittees and properly classifying them in the *Handbook*.

The material in this *Handbook* has been prepared by men who are all specialists and authorities in their particular field. They obtained the material either from their own researches or from sources considered trustworthy and reliable. The articles were carefully reviewed by *Metals Handbook Committee* and special reviewing committees. It is, however, recommended that the information in this *Handbook* should be interpreted by the reader in the light of his own personal experience and in accordance with his own plant equipment and practices.

It is desired to emphasize that the material published in this *Handbook* is not intended for specifications and should not be interpreted by the reader as such.

The American Society for Metals does not, by the publication of an article in this *Handbook*, insure anyone using such information against liability, nor does the Society assume any liability for infringement of any patent that may now exist or that may be issued later. Also, it should be understood that the publication of any article in this *Handbook* does not constitute a recommendation of any patent or proprietary rights that may be involved.

A considerable portion of this Handbook is devoted to a variety of subjects on nonferrous metallurgy. This is an important section of the Handbook and it is believed that it constitutes a section that meets a valuable need among the many readers. Material for the nonferrous section has been prepared and compiled by members of the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers through a co-operative arrangement with the American Society for Metals. The Nonferrous Data Sheet Committee of the Institute of Metals has completed a very successful and important program for this edition of Metals Handbook. The completion of this program has aided greatly in developing the nonferrous section of the Handbook. It contains more than ever before information on the properties, technology, and application of nonferrous metals and their alloys. The personnel of the Nonferrous Data Sheet Committee of the Institute of Metals Division was as follows: Jerome Strauss, Chairman; W. L. Fink; W. E. Remmers; E. E. Schumacher; E. M. Wise; and Lyall Zickrick.

We especially wish to express our thanks and appreciation to the members of Metals Handbook Committee, its predecessors, its subcommittees, to the individual authors, to the Nonferrous Data Sheet Committee of the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers, and the many reviewers who have given so generously of their time and technical information in the preparation of this Handbook.

We are indebted to Ralph Dowdell, Professor of Metallography, School of Mines and Metallurgy, University of Minnesota, and Miss Carrie Green, Teaching Assistant in Metallography, School of Mines and Metallurgy, University of Minnesota, for the preparation of the index. They have devoted much time and thought in the endeavor to prepare an adequate index for this volume. It is our hope and belief that their endeavors are successful.

The users of Metals Handbook will be rendering a service if they will point out any errors that may come to their attention so that corrections can be properly made in future printings.

Each member of the Society should feel free to offer his constructive criticisms and suggestions, all of which are an indispensable auxiliary to the preparation and enlargement of future editions of this Handbook. It is only by the continuation of such co-operation that we may expect to have Metals Handbook continue its growth in the future as it has in the past.

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Glossary of Selected Iron and Steel Terms and Definitions of Terms Relating to Heat Treatment Operations*

(Especially as Related to Ferrous Alloys)

Foreword to Definitions—In the development of the knowledge of heat treating operations some confusion has arisen concerning the terms commonly used. For example, the term “annealing” is applied by some to any operation of heating and cooling which results in softening, while as applied by others, the term does not mean softening primarily but describes a treatment consisting in heating above the upper critical temperature in steel and cooling very slowly. Similar confusion has for many years attended the use of the terms “hardening” and “tempering.”

In any attempt to define accurately commonly used terms, it is necessary to decide whether the terms are to relate to the operation performed, or to the properties thus determined; in general, the terms given will relate to the operations performed, though this is not always possible.

By critical temperatures, or by a critical temperature range, is meant those temperatures or that temperature range at which and in which iron-carbon alloys undergo transformation. Fig. 1 represents those schematically; all temperatures indicated are designated as transformation temperatures as determined on heating—this is the meaning of the *c* included in each term; it will be understood that Fig. 1 is not intended to give exact temperatures, for these vary with the rate of heating, are quite different on cooling, and vary with a number of factors. In Fig. 1 each line is appropriately designated; modern usage is veering toward the use of simple letters to designate the various lines, and these are also indicated in Fig. 1.

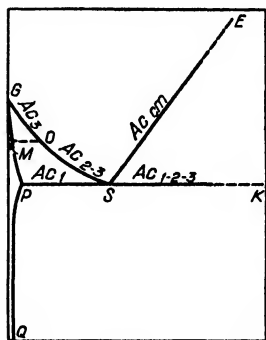


Fig. 1.

Acid Bottom and Lining—The inner bottom and lining of a melting furnace composed of materials having an acid reaction in the melting process. The materials may be sand, siliceous rock, or silica bricks.

Acid Brittleness—The brittleness induced in steel, especially wire or sheet, when pickled in dilute acid for the purpose of removing scale or upon electroplating. This brittleness is commonly attributed to the absorption of hydrogen.

Acid Steel—Steel melted in a furnace with an acid (siliceous) bottom and lining and under a slag which is dominantly siliceous.

Aging—The spontaneous change in properties of a metal which occurs at relatively low temperature after a final heat treatment or a final cold working operation. Aging is a process in which the trend is toward a restoration of real equilibrium, and away from an unstable condition induced by a prior operation. The fundamental reaction involved is generally one of precipitation, sometimes submicroscopic. The method employed to bring about aging consists of exposure to a favorable temperature subsequent to (a) a relatively rapid cooling from some elevated temperature (quench aging) or (b) a limited degree of cold work (strain aging).

Air Hardening Steel—An alloy steel which does not require quenching from a high temperature to harden, but which is hardened by simply cooling in air from above its critical temperature range.

Alloy—A mixture with metallic properties composed of two or more elements of which at least one is a metal.

Alloy Elements—Chemical elements comprising an alloy; in steels usually limited to the metallic elements added to steel to modify its properties.

Alpha Iron—See the article “Iron-Carbon Diagram” in this Handbook.

Amorphous—Noncrystalline.

Annealing—A heating and cooling operation implying usually a relatively slow cooling.

Note—Annealing is a comprehensive term. The purpose of such a heat treatment may be:

- (a) To remove stresses.
- (b) To induce softness.
- (c) To alter ductility, toughness, electrical, magnetic, or other physical properties.
- (d) To refine the crystalline structure.
- (e) To remove gases.
- (f) To produce a definite microstructure.

In annealing, the temperature of the operation and the rate of cooling depend upon the material being heat treated and the purpose of the treatment.

*Prepared by the Committee on Definitions: R. F. Mehl, Chairman; O. H. Mathewson, R. H. Aborn, and R. B. Schenck.

Certain specific heat treatments coming under the comprehensive term "annealing" are:

A. Full Annealing—Heating iron-base alloys above the critical temperature range, holding above that range for a proper period of time, followed by slow cooling to below that range.

Note—The annealing temperature is generally about 100°F. above the upper limit of the critical temperature range, and the time of holding is usually not less than 1 hr. for each inch of section of the heaviest objects being treated (see tool steel section in this Handbook for tool steel practice). The objects being treated are ordinarily allowed to cool slowly in the furnace. They may, however, be removed from the furnace and cooled in some medium which will prolong the time of cooling as compared to unrestricted cooling in the air.

B. Process Annealing—Heating iron-base alloys to a temperature below or close to the lower limit of the critical temperature range followed by cooling as desired.

Note—This heat treatment is commonly applied in the sheet and wire industries, and the temperatures generally used are from 1020-1200°F.

C. Normalizing—Heating iron-base alloys to approximately 100°F. above the critical temperature range followed by cooling to below that range in still air at ordinary temperature.

D. Patenting—Heating iron-base alloys above the critical temperature range followed by cooling below that range in air, or in molten lead or a molten mixture of nitrates or nitrites maintained at a temperature usually between 800-1050°F., depending on the carbon content of the steel and the properties required of the finished product.

Note—This treatment is applied in the wire industry to medium or high carbon steel as a treatment to precede further wire drawing.

E. Spheroidizing—Any process of heating and cooling steel that produces a rounded or globular form of carbide.

Note—The spheroidizing methods generally used are

(1) Prolonged heating at a temperature just below the lower critical temperature, usually followed by relatively slow cooling.

(2) In the case of small objects of high carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range.

(3) Tool steel is generally spheroidized by heating to a temperature of 1380-1480°F. for carbon steels and higher for many alloy tool steels, holding at heat from 1-4 hours and cooling slowly in the furnace.

F. Tempering—(also termed drawing)—Reheating hardened steel to some temperature below the lower critical temperature, followed by any desired rate of cooling.

Note—Although the terms "tempering" and "drawing" are practically synonymous as used in commercial practice, the term "tempering" is preferred.

G. Malleabilizing—An annealing operation performed on white cast iron partially or wholly to transform the combined carbon to temper carbon, and in some cases wholly to remove the carbon from the iron by decarburization.

Note—Temper carbon is free graphitic carbon in the form of rounded nodules composed of an aggregate of minute crystals.

H. Graphitizing—Graphitizing is a type of annealing for gray cast iron whereby some or all of the combined carbon is transformed to free graphitic carbon.

Austenite—See the article "Iron-Carbon Diagram" in this Handbook.

Banded Structure—A segregated structure of nearly parallel bands which run in the direction of working.

Bark—The decarburized skin or layer just beneath the scale found after heating steel in an oxidizing atmosphere.

Basic Bottom and Lining—The inner lining and bottom of a melting furnace composed of materials having a basic reaction in the melting process. The materials may be crushed burnt dolomite, magnesite, magnesite bricks, or basic slag.

Basic Steel—Steel melted in a furnace with a basic bottom and lining and under a slag which is dominantly basic.

Bessemer Process—A process for making steel by blowing air through molten pig iron contained in a suitable vessel. The process is one of rapid oxidation mainly of silicon and carbon.

Beta Iron—See the article "Iron-Carbon Diagram" in this Handbook.

Billet—See *bloom*.

Billet Mill—See *blooming mill*.

Binary Alloy—An alloy containing two elements, apart from minor impurities.

Black Annealing—A process of box annealing of sheets prior to tinning whereby a black color is imparted to the surface of the product.

Blast Furnace—A shaft furnace supplied with air blast, usually hot, for producing pig iron by smelting iron ore. The furnace is continuous in operation, the raw materials (iron ore, coke, and limestone) are charged at the top, and the molten pig iron and slag are collected at the bottom and are tapped out at intervals.

Bliater—A defect in metal produced by gas bubbles either on the surface or formed beneath the surface. Very fine blisters are called pinhead or pepper blisters.

Bliater Bar—Wrought iron bars impregnated with carbon and formerly used in the manufacture of crucible steel. Also called *bliater steel*.

Bloom (slab, billet, sheet bar)—Semifinished products of rectangular cross section with rounded corners, hot rolled from ingots. The chief differences are in cross sectional area, in ratio of width to thickness, and in their intended use. American Iron and Steel Institute Manual classifies general usage as follows:

Type	Width, in.	Thickness, in.	Cross Section Area, sq. in.
Bloom	Width equals thickness		36 (min.)
Billet	1½ (min.)	1½ (min.)	2¼-36
Slab	10+ (min.)	1½ (min.)	16 (min.)
Sheet bar	8-16	¼-2*	2-32*

*Calculated from weight range 7-54 lb. per lineal foot.

Rerolling quality blooms, slabs, and billets are intended for hot rolling into shapes, plates, strip, bars, and wire rod.

Forging quality blooms, billets, and slabs are intended for conversion into forgings.

Sheet bar is converted by rolling into sheet, black plate, and tin plate.

Blooming Mill—A mill used to reduce ingots to blooms, billets, slabs, or sheet bars. Depending upon the product, the mill is called a blooming mill (cogging mill in England), a billet mill, or a slabbing mill.

Blowhole—A hole produced during the solidification of metal by evolved gas which, in failing to escape, is held in pockets.

Blue Annealing—A process of annealing sheets after rolling. The sheets, if fairly heavy, are allowed to cool slowly after the hot rolling; if of lighter gage, as is usually the case, they are passed singly through an open furnace for heating to the proper annealing temperature. As the name indicates, the sheets have a bluish-black appearance.

Blue Brittleness—Brittleness occurring in steel when worked in the temperature range of 300-700°F., or when cold after being worked within this temperature range.

Box Annealing—Softening steel by heating, usually at a subcritical temperature, in a suitable closed metal box or pot to protect it from oxidation, employing a slow heating and cooling cycle; also called close annealing or pot annealing.

Bright Annealing—A process of annealing, usually with reducing gases, such that surface oxidation is reduced to a minimum, thereby yielding a relatively bright surface.

Burning—The heating of a metal to temperatures sufficiently close to the melting point to cause permanent injury. Such injury may be caused by the melting of the more fusible constituents, by the penetration of gases such as oxygen into the metal with consequent reactions, or perhaps by the segregation of elements already present in the metal.

Capped Steel—See *rimmed steel*.

Carbon Free—Metals and alloys which are practically free from carbon.

Carbon Steel—Steel which owes its properties chiefly to various percentages of carbon without substantial amounts of other alloying elements; also known as ordinary steel or straight carbon steel or plain carbon steel.

Carbonization—Coking or driving off the volatile matter from fuels such as coal and wood. (Carbonizing should not be confused with "carburizing".)

Carburizing (Cementation)—Adding carbon to the surface of iron-base alloys by heating the metal below its melting point in contact with carbonaceous solids, liquids, or gases.

Note—The term "carbonizing" is inadvisable and its use should be discouraged.

Case—The surface layer of an iron-base alloy which has been made substantially harder than the interior by the process of case hardening.

Case Hardening—A heat treatment or a combination of heat treatments in which the surface layer of an iron-base alloy is made substantially harder than the interior by altering its composition (carburizing or cyaniding, both of which are ordinarily followed by quenching, or by nitriding).

Cast Steel—Any object made by pouring molten steel into molds.

Casting Strains—Strains accompanied by internal stresses resulting from the cooling of a casting.

Cementite—See the article "Iron-Carbon Diagram" in this Handbook.

Chill Cast Pig—Pig iron cast into metal molds or chills. If a machine is used the product is known as machine cast pig.

Chipping—One method for removing seams and other surface defects with chisel or gouge, so that the defects will not be worked into the finished product. If the defects are removed by means of gas cutting the term "deseaming" or "scarfing" is used. Chipping is often employed simply to remove metal apart from defects.

Cleavage Plane—It is frequently possible to fracture a crystal of a metal or other substance so that the surface of fracture is smooth and plane, and always parallel to some definite crystallographic plane. This crystallographic plane is known as a cleavage plane. A substance may cleave on more than one crystallographic plane.

Cogging—Rolling or forging ingots to reduce them to blooms.

Cogging Hammer—A forging hammer used to reduce ingots to blooms.

Cogging Mill—See *blooming mill*.

Cold Rolling—See *cold working*.

Cold Shut—A defect produced during casting of molten metal which may result from splashing, surging, interrupted pouring, or the meeting of two streams of metal coming from different directions. It may be due to the freezing of one surface before the other metal flows over it, or to the presence of interposing surface films or dirt on cold sluggish metal, or to any factor that will prevent a perfect union where two surfaces meet that should fuse and blend.

Cold Working—Plastic deformation of a metal at a temperature low enough to insure strain hardening.

Combined Carbon—All the carbon in iron or steel which is combined with iron or alloying elements to form carbide.

Core—The interior portion of an iron-base alloy which is substantially softer than the surface layer as the result of case hardening.

Note—Also, that portion of a forging removed by trepanning; the inner part of a rolled section of rimmed steel as distinct from the rimmed portion or rim; a body of sand or other material placed in a mold to produce a cavity in a casting.

Cored Structure—A grain structure having composition gradients caused by the progressive freezing of the components in different proportions; the term "zonal structure" is in general preferable. In dendrites the cored or zonal structure is manifested by solvent-rich crystal axes and solute-rich interstices.

Critical Points—See the article "Iron-Carbon Diagram" in this Handbook.

Critical Range—See *critical points*.

Critical Temperature—See *critical points*.

Crop—The end or ends of an ingot containing the pipe or other defects which are cut off and discarded; also termed "crop end" and "discard."

Cup Fracture—The form of fracture of a tension test specimen when the exterior portion is extended and the interior relatively depressed, so that it looks like a cup, as the name implies. When only a portion of the exterior is extended the terms "half cupped" and "quarter cupped" are used, as the case may be.

Cupping—A defect in wire which causes it to break with a cup fracture accompanied by very little reduction of area.

Cyaniding—Surface hardening by carbon and nitrogen absorption of an iron-base alloy article or portion of it by heating at a suitable temperature in contact with a cyanide salt, followed by quenching.

Decalescence—The absorption of heat which occurs when steel is heated through the Ac₁ point.

Decarburization—The removal of carbon (usually refers to the surface of solid steel) by the (normally oxidizing) action of media which react with carbon.

Dendrite—A crystal formed by solidification, or in any other way, having many branches and a tree-like pattern; also termed "pine tree" and "fir tree" crystals.

Deseaming—See *chipping*.

Differential Heating—Heating conducted in such a way that various portions of an object attain different temperatures so that upon cooling different properties are produced.

Discard—See *crop*.

Dissolved Carbon—Carbon in solution in either the liquid or solid state.

Divorced Cementite—The cementite resulting from partial or complete spheroidization, frequently observed in some slowly cooled steels, particularly fine grained, aluminum killed steel.

Drawing Back—See *tempering under annealing*.

Elongation—The amount of permanent extension in the vicinity of the fracture in the tension test; usually expressed as a percentage of the original gage length, such as 25% in 2 in. It may also refer to the amount of extension at any stage in any process which continuously elongates a body, as in rolling.

Endurance Limit—A limiting stress, below which metal will withstand without fracture an indefinitely large number of cycles of stress. If the term is used without qualification, the cycles of stress are usually such as to produce complete reversal of flexural stress. Above this limit failure occurs by the generation and growth of cracks until fracture results in the remaining section.

Endurance Ratio—The ratio of the endurance limit for cycles of reversed flexural stress to the tensile strength.

Equilibrium—See the article "Iron-Carbon Diagram" in this Handbook.

Eutectic Alloy—The composition in an alloy system at which two descending liquidus curves in a binary system or three descending liquidus surfaces in a ternary system intersect at a point. Such an alloy has thus a lower melting point than neighboring compositions. More than one eutectic composition may occur in a given alloy system.

Eutectoid Steel—A steel of the eutectoid composition. Composition S on the iron-carbon diagram. This composition in pure iron-carbon alloys is 0.80% C, but variations from this composition are found in commercial (impure) steels, and particularly in alloy steels in which the eutectoid composition is usually lower.

Exfoliation—The spalling or flaking off of the outer layer of an object.

Fatigue—The phenomenon of the progressive fracture of a metal by means of a crack which spreads under repeated cycles of stress.

Fatigue Limit—Usually used as synonymous with endurance limit.

Ferrite—See the article "Iron-Carbon Diagram" in this Handbook.

Ferrite Ghost—A faint band of ferrite.

Ferroalloy—An alloy of iron with a sufficient amount of some element or elements, such as manganese, chromium, or vanadium, for use as a means of introducing these elements into steel by admixture to molten steel.

Fiber—A characteristic of wrought metal manifested by a fibrous or woody appearance of fractures and indicating directional properties. Fiber is caused chiefly by the extension in the direction of working of the constituents of the metal, both metallic and nonmetallic. This term also refers to the characteristic reorientation of the crystalline particles of the metal produced by a given deformation process; see "fibering" in the Glossary of Terms used in X-ray Metallography.

Fiber Stress—Local unit stress at a point or line on a section over which stress is not uniform, such as the cross section of a beam under a bending load.

Fin—See *flash*.

Finished Steel—Steel which is ready for the market without further work or treatment. Blooms, billets, slabs, sheet bars, and wire rods are termed semifinished.

Finishing Temperature—The temperature at which hot mechanical working of metal is completed.

Fir Tree Crystal—See *dendrite*.

Flakes (or "snow flakes")—Internal fissures in large steel forgings or massive rolled shapes. In a fractured surface or test piece they appear as sizeable areas of silvery brightness and coarser grain size than their surroundings. Sometimes known as "chrome checks" and (when revealed by machining) "hairline cracks." Not to be confused with "woody fracture."

Flash—A thin fin of metal formed at the sides of a forging or weld where a small portion of the metal is forced out between the edges of the forging or welding dies.

Forging Strains—Elastic strains resulting from forging or from cooling from the forging temperature.

Fracture—The irregular surface produced when a piece of metal is ruptured or broken.

Fracture Test—Breaking a piece of metal for the purpose of examining the fractured surface to determine the structure or carbon content of the metal or the presence of internal defects.

Free Ferrite—Ferrite formed from austenite on cooling, without simultaneous rejection of carbon.

Full Annealing—See *annealing*.

Fusible Alloys—A group of nonferrous alloys which melt at relatively low temperatures. They usually consist of bismuth, cadmium, lead, and tin in various proportions, and iron only as an impurity.

Gamma Iron—A crystal form of iron (face-centered cubic) stable between A_3 and A_4 . See the article "Iron-Carbon Diagram" in this Handbook.

Ghost, Ghost Lines, or Ghost Structure—See *ferrite ghost*.

Globular Cementite—See *spheroidal cementite*.

Grains—Individual crystals in metals.

Grain Growth—An increase in the grain size of metal.

Granular Pearlite (also globular pearlite and divorced pearlite)—A structure formed from ordinary lamellar pearlite by long annealing of steel at a temperature below but near to the lower critical point, causing the cementite to spheroidize in a ferrite matrix. Since "pearlite" connotes a lamellar structure, this name is not recommended; the word "spheroidite" has been proposed.

Granulation—The recrystallization of columnar crystals and dendrites in freshly solidified steel to more or less equiaxed grains at temperatures near the solidus.

Graphitizing—See *annealing*.

Hair Seam—See *seam*.

Hardening—Heating and quenching certain iron-base alloys from a temperature either within or above the critical temperature range for the purpose of producing a hardness superior to that obtained when the alloy is not quenched. Usually restricted to the formation of martensite.

Heat Tinting—Heating a specimen with a suitable surface in air for the purpose of developing the structure by oxidizing or otherwise affecting the different constituents.

Heat Treatment—An operation or combination of operations involving the heating and cooling of a metal or alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

Note—Heating and cooling for the sole purpose of mechanical working are excluded from the meaning of this definition.

Hot Shortness—Brittleness in metal when hot.

Hot Top—See *sinkhead*.

Hot Working—Plastic deformation of metal at a temperature high enough to prevent strain hardening.

Hypereutectoid Steel—A steel containing more than the eutectoid percentage of carbon; see *eutectoid steel*.

Hypoeutectoid Steel—A steel containing less than the eutectoid percentage of carbon; see *eutectoid steel*.

Impact Test—Tensile and bend impact tests or test specimens are described in other parts of the Handbook.

Inclusions—Particles of impurities, usually oxides, sulphides, silicates, and such which are mechanically held during solidification or which are formed by subsequent reaction of the solid metal.

Ingot—A special kind of casting for subsequent rolling or forging.

Ingot Iron—An open hearth iron very low in carbon, manganese, and other impurities.

Killed Steel—A steel sufficiently deoxidized to prevent gas evolution during solidification. The top surface of the ingot freezes immediately and subsequent shrinkage produces a central pipe. A *semikilled steel*, having been less completely deoxidized, develops sufficient gas evolution internally in freezing to replace the pipe by a substantially equivalent volume of rather deep-seated blowholes. (See section on Open Hearth Process.)

Lap—A surface defect appearing as a seam caused from folding over hot metal, fins, or sharp corners and then rolling or forging, but not welding, them into the surface.

Lap Weld—A term applied to a weld formed by lapping two pieces of metal and then pressing or hammering, particularly, to the longitudinal joint produced by a welding process for tubes or pipe in which the edges of the skelp are beveled or scarfed so that when they are overlapped they can be welded together. The product is known as lap weld or lap welded pipe.

Ledeburite—The cementite-austenite eutectic forming at point C on the iron-carbon diagram. During cooling the austenite in ledeburite may transform to ferrite and carbide-cementite. It is found in cast iron and high alloy steels such as high speed steel.

Liquidus—The line on a temperature-composition (phase) diagram of a binary system, or surface on a diagram of a ternary system, representing the temperatures at which freezing begins on cooling or melting ends on heating under equilibrium conditions.

Lüder's Lines (stretcher-strains, flow figures)—Elongated surface markings that appear on the surface of some materials, particularly iron and low carbon steel, when deformed just past the yield point. These markings lie approximately parallel to the direction of maximum shear stress and are the result of localized yielding. They consist of depressions when produced in tension and of elevations when produced in compression; they may be made evident by localized roughening of a polished surface or by localized flaking of scale from a scaled surface.

Lute—A mixture of fire clay used to seal up cracks between crucible and cover or between annealing box and cover to make a gas tight joint when heat is to be applied; also applied to the operation.

Macroscopic—Visible either with the naked eye or under low magnifications (up to about 10 diameters).

Macrostructure—The structure and internal condition of metals as revealed on a ground or polished (and sometimes etched) sample, by either the naked eye or under low magnifications (up to about 10 diameters).

Malleablizing—See *annealing*.

Martensite—A microconstituent or structure in quenched steel characterized by an acicular or needle-like pattern on the surface of polish. It has the maximum hardness of any of the decomposition products of austenite.

Note—Martensite is a transition lattice formed by the partial transformation of austenite. It is not an equilibrium lattice and thus not an equilibrium phase. The lattice is tetragonal.

Matrix—The ground mass or principal substance in which a constituent is embedded.

Mechanical Properties—Those properties that reveal the reaction, elastic and inelastic, of a material to an applied force, or that involve the relationship between stress and strain, for example, Young's modulus, tensile strength, fatigue limit. These properties have often been designated as physical properties, but the term mechanical properties is much to be preferred.

Mechanical Testing—Testing methods by which mechanical properties are determined.

Mechanical Working—Subjecting metal to pressure exerted by rolls, presses, or hammers, to change its form, or to affect the structure and therefore the mechanical and physical properties.

Metalloid—Originally a chemical element that has the physical characteristics of a metal such as metallic conduction and metallic luster, but which behaves chemically as both nonmetal and metal; that is, it reacts directly with other metals yet also combines with the halogens to form salts. Typical examples are arsenic, antimony, and tellurium. With increasing knowledge of metallic compounds the term has become less useful, and it is now considered obsolete. In metallurgical practice it has come to have a special meaning as applying to the elements such as C, Si, P, S, and Mn, which are commonly present in small amounts in iron and steel.

Modulus of Elasticity—The ratio, within the limit of elasticity, of the stress to the corresponding strain. The stress in pounds per square inch is divided by the elongation in fractions of an inch for each inch of the original gage length of the specimen.

Network Structure—A structure in which the grains or crystals of one constituent are partially or entirely surrounded with envelopes of another constituent. The appearance of an etched section through the crystals is that of a network.

Neumann Bands—Mechanical twins in alpha iron, in the form of narrow bands parallel to planes of the form {211}. Customarily formed only on deformation by impact, but in some alloys (silicon-ferrite) and particularly at low temperatures formed more readily, as in ordinary cold working processes.

Nitriding—Adding nitrogen to iron-base alloys by heating the metal in contact with ammonia gas, or other suitable nitrogenous material.

Note—Nitriding is conducted at a temperature usually in the range 935-1000°F. and produces surface hardening of the metal without quenching. See article on "Nitriding."

Normalizing—See *annealing*.

Overheating—Heating to such high temperatures that the grains have become coarse, thus impairing the properties of the metal.

Patenting—See *annealing*.

Pearlite—The lamellar aggregate of ferrite and carbide resulting from the direct transformation of austenite at Ar₁.

Note—It is recommended that this word be reserved for the microstructures consisting of thin plates or lamellae—that is, those that may have a pearly luster in white light. The lamellae can be very thin and resolvable only with the best microscopic equipment and technique.

Permanent Mold—A mold ordinarily of metal which is used repeatedly for the production of many castings of the same form. Not commonly applied to ingot molds.

Permanent Set—Permanent deformation.

Phosphorus Banding—See *ferrite ghost*.

Physical Properties—Those properties familiarly discussed in physics, exclusive of those described under mechanical properties; for example, density, electrical conductivity, coefficient of thermal expansion. This term has often been used to describe mechanical properties, but this usage is not recommended. (See mechanical properties.)

Physical Testing—Testing methods by which physical properties are determined. This term is also inadvisedly used to mean the determination of the mechanical properties.

Piercing—Producing a hole in metal by forcing an instrument through it. Usually refers to making steel tubes from solid steel bars.

Pig Iron—See the article "Cast Iron" in this Handbook.

Pine Tree Crystals—See *dendrite*.

Pinhead Blister—See *blister*.

Pipe—A cavity formed in metal (especially ingots) during the solidification of the last portion of liquid metal. Contraction of the metal causes this cavity or pipe.

Pit—A sharp depression in the surface of metal.

Pot Annealing—See *box annealing*.

Pouring—Pouring molten metal from the ladle into ingot molds or other types of molds (as, for example, in castings).

Process Annealing—See *annealing*.

Quaternary Alloy—An alloy containing four principal elements.

Quenching—Rapid cooling by immersion in liquids or gases or by contact with metal.

Recalcinescence—The liberation of heat when steel is cooling through the Ar₁ point.

Red Shortness—Brittleness in steel when it is red hot.

Reduction in Area—The difference between the original cross sectional area and that of the smallest area at the point of rupture. It is usually stated as a percentage of the original area; also called "contraction of area."

Refining Temperature or Heat—A temperature employed in heat treatment to refine the structure, in particular, the grain size. Usually just above Ac₃ in steel.

Regenerative Quenching—A double quenching of carburized objects to refine the case and core. The first quench is from a high temperature to refine the core, and the second quench is from a lower temperature to further refine and harden the case.

Rimmed Steel—An incompletely deoxidized steel normally containing less than 0.25% carbon and having the following characteristics: (a) During solidification an evolution of gas occurs sufficient to maintain a liquid ingot top ("open" steel) until a side and bottom rim of substantial thickness has formed. If the rimming action is intentionally stopped shortly after the mold is filled the product is termed *capped steel*. (b) After complete solidification, the ingot consists of two distinct zones: A rim somewhat purer than when poured and a core containing scattered blowholes with a minimum amount of pipe and having an average metalloïd content somewhat higher than when poured and markedly higher in the upper portion of the ingot.

Riser—See *sinkhead*.

Seab (Seabby)—A rough projection on a casting caused by the mold breaking or being washed by the molten metal, or occurring where the skin from a blowhole has partly burned away and is not welded.

Scarfing—See *chipping*.

Seam—A crack on the surface of metal which has been closed but not welded; usually produced by blowholes which have become oxidized. If very fine, a seam may be called a hair crack or hair seam; also see *cold shut* and *lap*.

Secondary Hardening—Hardness developed by tempering high alloy steels.

Self Hardening Steel—A steel carrying sufficient carbon or alloy content (or both) to form martensite through rapid heat removal from a locally heated portion (as in welding) by conduction into the surrounding cold metal. See also *air hardening*.

Semifinished—See *finished*.

Sheet Bar—See *bloom*.

Shortness—Brittleness in metal

Silky Fracture—A steel fracture having a very smooth fine grain or silky appearance.

Sinkhead or Hot Top (also called a **Riser** when applied to castings)—A heat insulated reservoir for excess metal on top of an ingot mold or casting mold which feeds the shrinkage of the ingot or the casting.

Skelp—A plate of steel or wrought iron from which pipe or tubing is made. This is done by rolling the skelp up longitudinally into shape and welding or riveting the edges together.

Slab—See *bloom*.

Slabbing Mill—A heavy plate mill usually of the two-high universal type.

Slip Bands—A series of parallel lines running across a crystalline grain and produced by deforming the body after the surface on which these lines appear has been polished. They are traces of the slip planes, or planes joining the displaced crystalline blocks or lamellae, and may be distinguished from twin markings by repolishing and etching: Twin markings will reappear, but slip lines will not.

Slip Plane—See *slip bands*

Soaking—Holding steel at an elevated temperature for the attainment of uniform temperature throughout the piece.

Solidification Range—Temperature range through which metal freezes or solidifies.

Solidus Line—The line on a phase diagram below which (at lower temperature) the alloy is entirely solid under equilibrium conditions.

Sonims—Solid nonmetallic inclusions in a metal or alloy.

Sorbite—A late stage in the tempering of martensite, when the carbide particles have grown so that the structure has a distinctly granular appearance. Further and higher tempering causes globular carbides to appear clearly.

Note—Many times the term sorbite is erroneously given to an imperfectly developed pearlite or mixed structure in steel.

Spalling—The cracking and flaking of small particles of metal from the surface.

Spheroidal or Spheroidized Cementite—The globular condition of iron carbide resulting from a spheroidizing treatment (see under *annealing*). The initial structure may be either pearlitic or martensitic.

Note—The term "spheroidized pearlite" should be avoided, even when the structure is undoubtedly the result of spheroidizing anneal of a pearlitic steel. The term "spheroidite" has been proposed.

Spheroidizing—See *annealing*.

Spiegel (also Spiegeleisen)—A pig iron containing 15-30% manganese and 4.5-6.5% carbon.

Stead's Brittleness—A condition of brittleness yielding rectangular transcrystalline fractures in the coarse grain structure produced by prolonged annealing of thin sheets of very low carbon steel previously rolled at a relatively low temperature (below 1300°F.).

Tapping—Removing molten steel from the melting furnace by opening the tap hole and allowing the steel to run into the ladle.

Teeming—See *pouring*. Usually refers to pouring of metal into molds.

Tempering—See *annealing*.

Temper Carbon—A form of graphite in iron-base alloys produced by heating below the melting point.

Ternary Alloy—An alloy containing three principal elements.

Troostite—A microconstituent of hardened and tempered steel which etches rapidly and therefore usually appears dark. It consists of a very fine aggregate of ferrite and cementite and is not resolved under the microscope.

Note—Two entirely different structures are frequently confused and called troostite. The nodular quick etching microconstituent, found in steels which are cooled just too slowly to be fully martensitic, can be resolved into very fine pearlite. It is recommended that the use of the term troostite or "quenching or nodular troostite" to denote this structure be avoided. "Temper troostite" is the first product of the tempering of martensite and consists of sub-microscopic particles of carbide in ferrite, and is frequently indistinguishable in general appearance from a quickly etching fine pearlite. If the word troostite is to be retained it should be reserved for temper troostite. It changes on higher tempering by indistinguishable degrees into sorbite.

Twin Crystals (twins, twinned crystals)—A crystal grain in which the crystal lattices of two parts are related in orientation to each other as mirror images across the interface, which is known as the twinning plane.

Twin Bands—In a polished and etched section, a band across a crystal grain, brought by twinning into relation with the main body of the grain as described above.

Widmanstätten Structure—When a new solid phase forms from a parent solid phase, such as ferrite from austenite, the new phase generally develops plates parallel to lattice planes of a single form in the parent phase, for example, the four families of octahedral planes in austenite. On the polished and etched surface the traces of these plates intersect in a geometrical pattern. Needles and polyhedra may also form. The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. Familiarly seen in cast steel and in overheated wrought steel when cooled rather rapidly, but may occur in any alloy in which a phase change occurs.

Wire Rod—A semifinished product from which wire is made. It is generally of circular cross section approximately $\frac{1}{4}$ in. in diameter.

Woody Fracture—A descriptive term for fracture of sound though dirty steel, frequently also reedy or conchoidal in appearance, and often containing discernable slag particles. Woody fractures sometimes contain many small silvery areas, too numerous and small to be correctly termed "flakes", and of a different nature.

Work Hardness—Hardness developed in metal resulting from cold working.

Yield Point—The load per unit of original cross section at which, in soft steel, a marked increase in deformation occurs without increase in load. In other steels and in nonferrous metals, "yield point" is the stress corresponding to some definite and arbitrary total deformation, permanent deformation or slope of the stress deformation curve; this is more properly termed the yield strength.

Yield Strength—Stress corresponding to some fixed permanent deformation such as 0.1 or 0.2% offset from the modulus slope.

Young's Modulus—See *modulus of elasticity*.

Glossary of Terms Used in X-Ray Metallography

By Dr. L. W. McKeehan*

This glossary is primarily intended for those who, while not themselves conducting experiments or tests, in which X-rays are used, have occasion to consult publications in this field. It may have secondary value to those who prepare such publications and who wish to use terms that are unambiguous. A part of the glossary has appeared in the Proceedings of the A.S.T.M.¹ with a report of its Committee on X-Ray Metallography. It is here revised and extended and is supplemented by a list of German terms with their English equivalents. English compound nouns have generally been hyphenated, although the hyphen tends to drop as the terms become more familiar.

A (abbreviation)—Ångström unit, 10^{-8} cm.; also written Å.U., Å.U., Å.

absorber (for X-rays)—A sheet of matter placed between the source of X-radiation and the place where it is detected or measured. When the absorber contains elements so chosen that the intensity of X-rays with undesired wave lengths is especially reduced, the absorber is usually called a filter.

absorption coefficient (for X-rays in a substance)—The rate of decrease, per unit distance traversed in a substance, of the natural logarithm of the intensity of a parallel beam; usually written μ .

absorption-limit—See limit.

amorphous—Without crystal structure, so that the X-ray diffraction-pattern is like that of a liquid.

angle—See glancing angle.

Ångström unit—Å, 10^{-8} cm.

anisotropic—Having different properties in different directions.

anticathode (in X-ray tubes)—The part of the anode which receives most of the cathode-rays, and in which the target, if any, is mounted.

asterism (in X-ray diffraction-patterns)—The appearance of streaks or bands approximately along radii of the pattern.

axial ratio (in crystals)—In the tetragonal system and in the hexagonal division of the hexagonal system, the ratio of the parameter for the principal crystallographic axis of highest multiplicity to the parameter for either one of the other principal axes, usually written $C = c/a$; in less symmetrical systems the continued ratio of all three parameters, usually written $a:b:c$.

axis (crystal)—One of three noncoplanar intersecting lines, fixed with respect to a crystal, which meet any crystal plane at points whose distances from the intersection of the axes, in terms of three parameters (a , b , and c), one for each axis, are in the ratios of small integers; the principal crystal axes are those about which the symmetry is the highest possible to the crystal considered. Less properly, the length of an edge of the unit cell. See parameter.

axis of symmetry—A line in a crystal about which a rotation through $360^\circ/N$, where N is 2, 3, 4 or 6, with or without a translation parallel to the line and with or without a reflection in a plane perpendicular to the line, replaces every element (point, line, and plane) of the crystal by an equivalent element. The axis is said to be N -fold and is a rotation-axis if neither translation nor reflection is involved, is a screw-axis if any other than a primitive translation is involved, and is a rotatory-reflection-axis (N not equal to 3) if reflection is involved.

back reflection—X-ray diffraction at deviations near 180° , especially useful in precise measurement of interplanar distances.

balanced filters (for X-rays)—A pair of filters adjusted to give the same absorption except in the range of wave lengths lying between their characteristic absorption-limits. When used alternately the difference in effect, if any, is due to X-rays having wave lengths in this range.

basal plane—In tetragonal and hexagonal crystals, a plane perpendicular to the c -axis.

beam (X-ray)—A nearly parallel group of X-rays from a common source.

body—See bulb.

body-centered (concerning space-lattices)—Having the equivalent lattice-points at the corners of the unit cell, and at its center; sometimes called centered, or space-centered.

Bragg equation (for X-ray reflection)—The equation $n\lambda = 2d\sin\theta$; see also reflection.

Bragg method (for X-ray or crystal analysis)—Using monochromatic or polychromatic X-rays and a single crystal of large size rotated through a small angle about an axis lying in a crystal face.

bulb (in X-ray tubes)—The glass (or other pressure-tight) part; when of metal, more usually called the body.

calcite—Natural rhombohedral CaCO_3 , the primary standard crystal used in X-ray spectrometry.

cassette (in X-ray spectrographs)—A box for holding a photographic film or plate in position to receive the X-ray diffraction-pattern.

cell—See unit cell.

centered (concerning space-lattices)—Body-centered.

channel (in X-ray spectrographs)—A collimating system consisting of a hole through a thick piece of metal (usually in two parts to permit cleaning).

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¹"Proceedings," A.S.T.M., v. 26, pt. 1, p. 582, 1926.

chaotic—See orientation.

characteristic X-rays—Series of monochromatic X-rays which are emitted (in addition to heterochromatic X-radiation) by a particular element when exposed to cathode-rays (or X-rays) of sufficiently high energy.

close-packed (concerning atomic arrangement in crystals)—Having one of the two possible arrangements, one cubic and one hexagonal, in which equal hard spheres can be made to occupy the least total volume, and, by extension, having any of the hexagonal arrangements derived from the second of these by expansion or contraction of the hexagonal axis. See face-centered and hexagonal close-packed.

coefficient—See absorption coefficient, mass-absorption coefficient, mass-scattering coefficient

collimate—To isolate a parallel, or nearly parallel, beam of rays, as by slits, pinholes, or a channel

continuous spectrum—Heterochromatic X-rays.

Coolidge (concerning X-ray tubes)—Having a high vacuum and a hot-wire cathode.

covering-operation—A general name for translations, symmetry-operations, and their combinations in extended structures by which every element (point, line, and plane) of the structure is replaced by an equivalent element. Besides translations and symmetry-operations there are screw-rotations about screw-axes and glide-reflections in glide-reflection-planes.

critical (concerning voltage, wave length or frequency)—Limiting; see limit.

cross-direction (in rolled metal)—The direction parallel to the axes of the rolls during rolling

crystal (noun)—A coherent piece of matter all parts of which have the same anisotropic arrangement of atoms; in metals usually synonymous with grain and crystallite.

crystal (adjective)—Of, or pertaining to, crystals.

crystal analysis—The determination of crystal structure.

crystal unit—Unit of structure.

crystalline—Composed of crystals.

cubic-centered (concerning space-lattices)—Body-centered cubic

cubic (concerning crystals)—Having nonparallel 3-fold axes of symmetry, with other symmetry-elements. Sometimes called isometric or regular. The typical cubic crystal has three equivalent axes (2-fold or 4-fold) mutually perpendicular, and the common parameter is usually written a (or a_0).

dated (concerning X-ray diffraction-patterns from crystal aggregates)—Made up of separately distinguishable images of the source.

Debye-Scherrer method (for X-ray crystal analysis)—Using a monochromatic (or polychromatic) X-ray beam defined by pinholes, an aggregate of small crystals oriented more or less completely at random and a photographic film bent into an almost complete cylinder with its axis perpendicular to the X-ray beam at the crystalline specimen; practically indistinguishable from the Hull method; sometimes called the powder method.

define (X-rays)—To limit in angle, as by slits or pinholes; to collimate.

deviation (X-ray)—The angle between the direction of incidence (produced through the substance) and the direction of diffraction; twice the glancing angle of incidence; usually written 2θ .

diagram (for X-ray diffraction-patterns)—A representation, either a photograph as taken, or a projection therefrom; for example, the index-diagram.

diamond-cubic (concerning atomic arrangements)—Similar to the diamond in having two face-centered cubic arrangements of atom-centers either of which is displaced with respect to the other by one-fourth of the diagonal of the unit cube.

diffraction (X-ray)—The deviation of an X-ray beam by scattering from atoms which have some regularity of arrangement or spacing.

diffraction-pattern (X-ray)—The totality of the intersections, with a plane or other surface, of the beams diffracted by a crystal or by a crystalline aggregate.

discontinuity (in absorption)—The ratio between absorption coefficients at a limit.

doublet (in characteristic X-ray spectra)—A pair of lines from the same element which differ little in wave length; for example, the $K\alpha$ -doublet, $K\alpha_1$, and $K\alpha_2$.

electron X-ray tube—An X-ray tube in which the current is maintained by thermionic emission from a hot cathode. See Coolidge.

end-centered (concerning orthorhombic space-lattices)—Having equivalent points at the corners of the unit cell and at the centers of the pair of opposite faces perpendicular to the c -axis. Same as side-centered with a different choice of axes.

equivalent (concerning points, lines, planes, and atoms)—Being interchangeable by the covering-operations appropriate to the structure.

excite (X-rays)—To cause to be emitted.

exposure (to X-rays)—The time-integral of the intensity; with X-ray tubes of the same kind and operated under the same conditions the exposure is proportional to the product of the electron current through the tube by the time of operation.

face (crystal)—A natural surface, or a cut surface parallel to a possible natural surface.

face-centered (concerning cubic space lattices)—Having equivalent points at the corners of the unit cell and at the centers of its six faces. A face-centered cubic space-lattice is characteristic of one of the close-packed arrangements of equal hard spheres.

family (of crystal planes)—The planes in any one crystal which have common indices.

fiber-axis—See fibering.

fiber-diagram—An X-ray diffraction-pattern, or a chart prepared therefrom, showing the existence of fibering or measuring its completeness.

- fibering** (in crystalline aggregates)—The state of a crystalline aggregate in which the preferred orientations are obtained by rotation about a line, the fiber-axis. If fibering is complete all azimuths about the fiber-axis are equally probable. If fibering is incomplete the preferred orientations may reduce to a small number and the notion of fibering loses its value. Besides simple fibering there may be helical fibering in which the fiber axis has all the orientations assumed by the tangent to a helix of constant pitch. In ring-fibering the pitch of the helix is zero.
- filter** (for X-rays)—A sheet of matter selectively absorbing secondary or other undesired X-rays. See also balanced filters.
- fluorescent screen** (for X-rays)—A sheet of matter (usually mounted on paper or other non-absorbent material) which emits visible or actinic light when exposed to X-rays.
- fluorescent X-rays**—Characteristic X-rays excited by X-rays.
- focus** (in X-ray tubes)—The spot on the target where the cathode rays are concentrated and which is therefore the principal source of X-rays; its shape and size are controllable by design.
- focusing** (concerning methods of X-ray or crystal analysis)—Using such a shape and position of sample and position of source that the diffracted X-rays from many (or all) parts of the sample fall close together in the diffraction-pattern; such methods permit the use of wide beams and require relatively short exposures. See Bragg method and Seemann-Bohlin method.
- form** (for equivalent crystal planes or lines)—Having the same indices, except for sign or order, for example, the planes (110), (101) in a cubic crystal are both of the form {110}; the planes (110), (101) in a tetragonal crystal are not of the same form. The lines [210], [120], [012] in a cubic crystal are of the form $\langle 210 \rangle$.
- frequency** (X-ray)—Measured by the equation $\nu = c/\lambda$, wherein c is the velocity of propagation of light (3×10^{10} cm. per sec.) and λ is the wave length in centimeters.
- frequency-factor** (for crystal planes of a form)—The number of different families of planes having the same form.
- gas X-ray tube**—An X-ray tube in which the current is initiated by ionization of residual gas at a pressure of the order of 10^{-3} mm. of mercury. This gas pressure must be kept within narrow limits during operation.
- general** (concerning X-radiation)—Heterochromatic.
- glancing angle**—The angle between the incident X-ray beam and the crystal planes from which reflection takes place, however these may be inclined to the bounding surface of the crystal usually written θ .
- glide-reflection-plane**—See plane of symmetry.
- gnomonic projection**—A projection in which each plane of a crystal is represented by the point in which the perpendicular let fall upon it from a fixed point meets the plane of the projection.
- goniometer**—An instrument for measuring angles or for setting objects in known orientations. Spectrographs and spectrometers are goniometers of a special sort.
- grating-constant** (in crystals)—Interplanar distance.
- grating-space** (in crystals)—Interplanar distance.
- halo** (in X-ray diffraction patterns)—A diffuse circular band.
- hard** (concerning X-rays)—Having great penetrating power, short wave length, high frequency.
- hemihedral** (concerning crystals)—Having but one-half of the symmetry-elements possible to the crystal system in which the crystal belongs; having different properties in opposite directions, or on opposite faces, or lacking symmetrically opposite faces.
- heterochromatic** (concerning X-rays)—Having a continuous series of wave lengths, as from a tube operated below the critical voltage for its target.
- heterogeneous** (concerning X-rays)—Heterochromatic.
- hexagonal** (concerning crystals)—Having parallel 6-fold rotation-axes of symmetry, or a single set of parallel 3-fold rotation-axes of symmetry with planes of symmetry perpendicular thereto, and with or without other symmetry-elements. The typical hexagonal crystal has two equal axes $b = a$ inclined at the angle 120° and a third axis (c) perpendicular to their plane.
- hexagonal close-packed** (concerning atomic arrangements in crystals)—Having atoms at the corners of the hexagonal unit cells, which are right prisms with rhombic bases, and at the centers of those (isosceles) triangular prisms which are similarly located halves of the hexagonal unit cells. The two sets of atoms are not crystallographically equivalent. If the atoms are arranged like hard equal spheres in contact, $C = 1.633$ or $2\sqrt{3}/3$.
- holohedral** (concerning crystals)—Having all the symmetry-elements possible to the crystal system in which the crystal belongs.
- homogeneous** (concerning matter)—Having the same properties in every small region containing many atoms (but not necessarily isotropic).
- homogeneous** (concerning X-rays)—Monochromatic.
- Hull method** (for X-ray crystal analysis)—Using a monochromatic (or polychromatic) X-ray beam defined by slits (or pinholes), an aggregate of small crystals oriented more or less completely at random and a photographic plate or a photographic film (if the latter, bent around a cylinder with its axis perpendicular to the X-ray beam at the crystalline specimen); practically indistinguishable from the Debye-Scherrer method; sometimes called the powder method.
- identity-period** (along a crystal line)—A primitive translation.
- image** (in X-ray diffraction-patterns)—By analogy with optics, a recognizable copy of the source of X-rays or of any aperture defining the X-ray beam.
- index-diagram**—A chart based upon an X-ray diffraction-pattern and permitting the assignment of indices to the families of planes responsible for the intensity maxima in the pattern.
- indices**—See Miller indices, Miller-Bravais indices, line-indices.

- intensifier** (for X-rays)—A substance placed in, on, or under a photographic emulsion or a fluorescent screen, or used in photographic development, to make the effects of X-rays more conspicuous.
- intensifying factor** (for X-ray intensifiers)—The ratio between the exposure when no intensifier is used to the exposure, for the same effect, when the intensifier is used, all other conditions remaining unaltered.
- intensifying screen** (in X-ray spectrographs)—A separately mounted intensifier.
- intensity** (X-rays)—The flux of energy per unit of time and per unit of cross-section perpendicular to the direction of propagation.
- interplanar distance** (in crystals)—The perpendicular distance between the nearest equivalent planes of a family; usually written d . The indices of the planes may be written as a subscript, for example, d_{100} .
- inversion**—A symmetry operation by which each point of a structure is replaced by a point at the same distance from a fixed point (the inversion-center) but in the opposite direction therefrom. See also symmetry-operation.
- ionization method**—Any method of X-ray or crystal analysis which depends upon measuring the electrical conductivity of a gas exposed to the diffracted X-rays; great accuracy in angular measurement is possible, but not easy.
- isometric** (concerning crystals)—Cubic.
- isotropic**—Having the same properties in every direction.
- K**—The letter used to designate the series of characteristic X-rays having, for each element, the shortest wave lengths; Greek letters and Arabic subscripts are used to distinguish the lines of the K-series; for example copper $K\alpha$, molybdenum $K\beta$, L and M are used to designate characteristic groups of X-rays of successively greater wave length, but these are rarely used in crystal analysis.
- lattice**—Space-lattice. Lattice-lines and lattice-planes are lines and planes so chosen as to pass through more than one lattice-point, and noncollinear lattice-points respectively.
- Laue method** (for crystal analysis)—Using heterochromatic X-rays, a small fixed crystal and a plane screen, usually a photographic plate; the Laue spot is the image (of a pinhole or of the small crystal itself) characteristic of the resulting diffraction-pattern.
- layer-line** (in revolving-crystal and oscillating-crystal methods)—A row of spots due to families of planes equally inclined to the axis of rotation or oscillation. Compare with side spectrum, zero spectrum.
- limit** (in voltage, wave length or frequency of X-rays)—A value, characteristic of the particular chemical element in question, on the two sides of which excitation, absorption, photographic effect, or the like, have sharply different values.
- line** (crystal)—A possible edge of a crystal.
- line** (in X-ray diffraction-patterns)—A straight or slightly curved narrow region of maximal intensity.
- line** (X-ray)—A group of monochromatic X-rays, not necessarily collimated.
- line-focus** (in X-ray tubes)—A focus with one dimension reduced to such an extent that the focus approximates to a segment of a straight line on the target in the plane determined by the axis of the tube and the direction from the target to the irradiated object. (This secures the advantages of a point source of X-rays without extreme local heating).
- line-indices**—The smallest integers proportional to the coordinate-differences, in terms of the parameters (a , b , and c), between equivalent points lying on a crystal line; written, in general [HKL], in particular, for example [210]; in cubic crystals the line $[pqr]$ is perpendicular to the plane (pqr) .
- mass-absorption coefficient** (for X-rays in a substance)—The rate of decrease, per unit mass traversed, of the natural logarithm of the intensity of a parallel beam; usually written μ/ρ . It is often more convenient than the absorption-coefficient because its use does not require knowledge of the density ρ . See also mass-scattering coefficient.
- mass-scattering coefficient** (for X-rays in a substance)—The rate of decrease, per unit mass traversed, of the natural logarithm of the intensity of a parallel beam, due to scattering alone; usually written σ/ρ ; the excess of the mass-absorption coefficient, μ/ρ , over σ/ρ is called the true mass-absorption coefficient, μ'/ρ .
- Miller indices** (for crystal planes)—The smallest integers proportional to the reciprocals of the intercepts, in terms of the parameters (a , b , and c), of the plane on the three crystal axes; written, in general, (hkl) , in particular, for example (210); see also form.
- Miller-Bravais indices** (for crystal planes in the hexagonal division of the hexagonal system only)—The smallest integers proportional to the reciprocals of the intercepts, in terms of the parameters (a , a , a , and c), of the plane on the four axes; written, in general (hkl) , in particular, for example (1120); the index for the hexagonal axis is always written last; $k = -(h + l)$ and may be replaced by a period, thus (1120) and (11.0) are the same. Any two of the three equivalent axes 120° apart in the basal plane together with the fourth axis are crystallographically sufficient, but the use of four axes makes it easier to recognize planes of the same form.
- monochromatic** (concerning X-rays)—Having only a single wave length.
- monoclinic** (concerning crystals)—Having only parallel 2-fold axes of symmetry, or parallel planes of symmetry, or both of these with the axes perpendicular to the planes. The typical monoclinic crystal has three unequal axes, only one of which is perpendicular to two others. The unique axis is usually taken as the b -axis.
- multiplicity** (for axes of symmetry)—The value of N if the axis is N -fold.

- order** (in X-ray reflection)—The integral value of n in the equation $n\lambda = 2d \sin \theta$.
- orientation** (crystal)—Arrangement in space of the axes of a crystal; every crystal must at every moment have a definite orientation, only aggregates, in space or in time, can possess chaotic orientation; if not chaotic some one or more orientations must be preferred.
- orthohexagonal** (concerning crystal axes)—A set of mutually perpendicular axes for hexagonal crystals. In terms of the more usual hexagonal parameters (a , a , c) the orthohexagonal parameters are $a\sqrt{3}$, a , c .
- orthorhombic** (concerning crystals)—Having only parallel 2-fold axes of symmetry, with planes of symmetry parallel to the axes or with additional 2-fold axes perpendicular thereto, or with both. The typical orthorhombic crystal has three unequal axes mutually perpendicular.
- oscillating-crystal method** (for X-ray or crystal analysis)—Using a single crystal rotating at constant speed, but alternately in both directions, through less than a complete rotation (usually much less).
- parameter** (in crystals)—A characteristic magnitude defining the unit cell or the position of a point within it. The edges of the unit cell, a , b , c , and the angles, α (between b and c), β (between c and a), γ (between a and b), are its parameters. The edge of the unit cube, a_0 , is the single parameter of a cubic lattice. When the fractional co-ordinates of a point within the unit cell may vary the values of these fractions: x , y , z , are parameters of the structure.
- pattern**—Diffraction-pattern.
- photogoniometer**—An X-ray goniometer with photographic registration.
- pinhole**—A small round hole used to define a beam of X-rays.
- plane** (crystal)—A possible face of a crystal.
- plane of symmetry**—A plane in a crystal in which a reflection, with or without a translation parallel to the plane, replaces every element (point, line, and plane) of the crystal by an equivalent element. The plane is a reflection-plane if no translation is involved, and is a glide-reflection plane if translation is involved.
- point-group**—A limited group of points (from 1 to 48 in number) possessing the same symmetry-elements as one of the 32 possible classes of crystals.
- pole-figure** (for crystalline aggregates)—A stereoscopic projection showing the preferred orientations of the normals to planes of a given form.
- polychromatic**—Having several distinct wave lengths, for example, the characteristic X-rays from a single element.
- powder method** (for X-ray or crystal analysis)—Using a loose aggregate of small crystals with chaotic orientation; applied, early but somewhat illogically, to methods using solid metals composed of crystalline aggregates; see Debye-Scherrer method, Hull method.
- preferred**—See orientation.
- primary** (concerning X-rays)—Emitted directly from the anticathode in the X-ray tube.
- primitive**—See translation.
- principal spectrum** (in revolving-crystal and oscillating-crystal patterns)—Zero spectrum.
- pseudocrystalline**—Possessing regularities of structure which result in a diffraction-pattern unlike that of a liquid or an amorphous solid, although true crystals are not present, for example, stretched rubber is pseudocrystalline.
- radiography**—The use of X-rays in studying the macrostructure of single objects or assemblies (internal boundaries, inclusions, variations in density or composition).
- random** (concerning orientation)—Chaotic.
- rating** (for X-ray tubes)—The product of the allowable current by the (peak) operating voltage.
- ratio**—See axial ratio.
- reciprocal lattice** (for a crystal)—A group of points so arranged about a center that the line joining each point to the center is perpendicular to a family of planes in the crystal, and its length is inversely proportional to their interplanar distance.
- reflection** (X-ray)—Diffraction considered as due to scattering by crystal planes as units, these being the reflecting planes; monochromatic X-rays are reflected only when $n\lambda = 2d \sin \theta$, where n is order, λ wave length, d , interplanar distance, and θ , glancing angle of incidence upon the planes considered.
- reflection-plane**—See plane of symmetry.
- regular** (concerning crystals)—Cubic.
- revolving-crystal method** (for crystal analysis)—Using a small single crystal rotating uniformly through many complete rotations during the time of the exposure.
- rhombohedral** (concerning crystals)—Having parallel 6-fold rotatory-reflection-axes, or a single set of parallel 3-fold rotation-axes, in either case without planes of symmetry perpendicular thereto, and with or without other symmetry-elements. The typical rhombohedral crystal has three equal axes ($c = a$, $b = a$) mutually inclined at an angle α not usually equal to 90° .
- rock salt**—Natural (cubic) NaCl, the secondary standard crystal used in X-ray spectrometry.
- rolling-direction** (in rolled metal)—The direction, in the plane of the sheet, perpendicular to the axes of the rolls during rolling.
- rotation-axis**—See axis of symmetry.
- rotation-diagram**—A chart used in assigning indices to families of planes giving spots in the diffraction-patterns obtained in revolving-crystal or oscillating-crystal methods for crystal analysis.
- rotatory-reflection-axis**—See axis of symmetry.
- scattering** (X-ray)—The re-emission of X-rays from irradiated matter, without change of wave-length (except as modified by the Compton effect, which is negligible in crystal analysis); it takes place in all directions with respect to the incident X-rays, but more intensely (or more often) in some directions than in others.

- screen** (in X-ray spectrographs)—A flat or curved surface on which a diffraction-pattern may be observed, for example, a fluorescent screen; sometimes, but not so properly, a shield.
- screw-axis**—See axis of symmetry.
- secondary** (concerning X-rays)—Emitted elsewhere than from the anticathode.
- secondary spectrum** (in revolving-crystal and oscillating-crystal patterns)—Side spectrum.
- Seemann-Bohlin method** (for crystal analysis)—Using a monochromatic (or polychromatic) X-ray beam of wide angular aperture, an aggregate of small crystals oriented more or less completely at random and spread on a cylinder an element of which also passes along the single slit defining the X-ray beam, and a photographic film bent to fit another segment of the same cylinder; it is a focusing method.
- series** (in X-ray spectra)—A group of characteristic X-rays having the same excitation-limit, distinguished as K-series and L-series. See also K.
- shield** (in X-ray spectrographs)—A plate, block, or the like, which prevents X-rays (usually secondary) from reaching the measuring or detecting device; a complete absorber.
- shutter** (in X-ray spectrographs)—A removable shield.
- side-centered** (concerning orthorhombic space-lattices)—Having equivalent points at the corners of the unit cell, and at the centers of the pairs of opposite faces perpendicular to the a-axis and to the b-axis. Same as end-centered with a different choice of axes.
- side spectrum** (in revolving-crystal and oscillating-crystal patterns)—A row of spots due to planes equally inclined to the axis of rotation or oscillation, but not parallel thereto. Compare with layer-line, zero spectrum.
- simple** (concerning space-lattices)—Having equivalent points only at the corners of the unit cell.
- slit**—A narrow opening with parallel sides, used to define a beam.
- slit-system**—A series of slits used to define a beam and to shield against secondary X-rays.
- slitless spectrograph**—Wedge-spectrograph.
- soft** (concerning X-rays)—Having little penetrating power, long wave length, low frequency
- source** (X-ray)—See focus.
- space-centered** (concerning space-lattices)—Body-centered.
- space-group**—An infinitely extended group of points possessing the same symmetry-elements and the same translations as one of the 230 different arrangements theoretically possible for atoms in crystals. The great number of space-groups as compared with point-groups is due to the fact that a different location in space for the same symmetry-elements is possible in the space-group but not in the point-group.
- space-lattice** (crystal)—A system of equivalent points formed by the intersections of three sets of planes parallel to pairs of principal axes; the space-lattice may be thought of as formed by the corners of the unit cells. See translation-group
- spacing** (between crystal planes)—Interplanar distance.
- spectrograph** (X-ray)—An instrument using an extended surface—a photographic plate or film, or a fluorescent screen—for receiving the X-ray diffraction-pattern
- spectrometer** (X-ray)—An instrument using a movable measuring device for exploring the X-ray diffraction-pattern.
- spectrum** (X-ray)—A distribution of X-rays along a line in accordance with wave length, or a group of X-rays so distributable. The set of layer-lines furnished by the revolving-crystal method is sometimes called the complete spectrum. See also side spectrum, zero spectrum
- stereographic projection**—A projection in which each plane of a crystal is represented by the point in which a perpendicular let fall upon it from a fixed point meets a sphere centered at the fixed point, and these representative points on the sphere are then represented in turn by the points in which lines drawn to them from the pole of a great circle of the sphere meet the diametral plane through the great circle.
- structure**—The arrangement of parts; especially, in crystals, the shape and dimensions of the unit cell and the number, kinds and positions of the atoms within it.
- symmetry**—See axis of symmetry, inversion, plane of symmetry.
- symmetry-element**—A general name for axes of symmetry, planes of symmetry and centers of inversion.
- symmetry-operation**—A geometrical operation which interchanges equivalent elements (points, lines, and planes) of a rigid geometrical figure. The possible symmetry-operations are rotations about rotation-axes passing through the center of the figure and reflections in reflection-planes passing through the same point. A rotary-reflection is a compound operation in which the rotation-axis must be perpendicular to the reflection-plane. An inversion is equivalent to a 2-fold rotatory-reflection about any rotatory-reflection-axis.
- system** (crystal)—One of the 6 classes into which the 32 possible types of crystal and the 230 possible types of structure have been divided on the basis of symmetry. They are triclinic, monoclinic, orthorhombic, tetragonal, hexagonal (including rhombohedral and hexagonal divisions), and cubic.
- target** (in X-ray tubes)—The part of the anticathode, wholly or predominantly of a single metal, or coated with a substance to be analyzed, where the focus lies.
- tetartohedral** (concerning crystals)—Having but one-fourth of the symmetry-elements possible to the crystal system in which the crystal belongs.
- tetragonal** (concerning crystals)—Having parallel 4-fold axes of symmetry but no 3-fold axes of symmetry. The typical tetragonal crystal has two equal axes ($b = a$) perpendicular to each other and to a third axis (c).
- translation** (in a crystal or space-group)—A displacement parallel to a crystal line. A primitive translation is the least translation, without accompanying rotation or reflection, which replaces every element (point, line, and plane) by an equivalent element. Suitable fractional parts of

- a primitive translation may be combined with rotation or reflection in screw-rotations and glide-reflections.
- translation-group**—An infinitely extended group of points possessing the same translations as one of the 14 possible space-lattices in crystals.
- transmission method** (for X-ray or crystal analysis)—Having the diffracted X-rays emergent from a surface which does not face the source.
- triline** (concerning crystals)—Having no symmetry-elements, or only inversion-centers. The typical triclinic crystal has three unequal axes no two of which are perpendicular.
- uniform** (concerning X-ray diffraction-patterns)—Not dashed.
- unit cell** (in crystals)—The least parallelepiped which possesses the full symmetry of the crystal, and repetition of which without change of orientation builds up a crystal of any size.
- unit cube** (in crystals)—The unit cell in cubic crystals.
- unit of structure** (in crystals)—The group of atoms included by the unit cell, especially if the arrangement of the group indicates chemical relations between its members.
- wave length** (X-ray)—The value of λ in the equation, $\lambda = \frac{2d \sin \theta}{n}$; wherein d is the interplanar distance in a crystal which reflects the X-rays at the glancing angle θ in the n th order.
- wedge-spectrograph**—An X-ray spectrograph (due to Seemann) in which the beams of incident and diffracted X-rays are limited by a wedge brought into contact with a face of the crystal; also called slitless spectrograph.
- Weissenberg photogoniometer**—A photogoniometer with a cylindrical film so shielded and axially advanced during exposure that the spots of a single layer line are consecutively recorded along its direction of travel.
- white** (concerning X-rays)—Heterochromatic.
- X** (abbreviation)—X-unit, 10^{-11} cm.; also written X.U.
- X-radiation**—X-rays in general, especially when their direction of propagation is not emphasized.
- X-ray** (adjective)—Of or pertaining to X-rays.
- X-ray analysis**—The measurement of X-ray wave lengths and intensities
- X-ray tube**—An assembly of cathode, anticathode, and bulb (or body) suitable for the production X-rays.
- X-rays**—Light-rays, excited usually by the impact of cathode-rays on matter, which have wave lengths between about 10^{-6} cm., and 10^{-9} cm.; also written x-rays; same as Röntgen-rays.
- zero spectrum** (in revolving-crystal and oscillating-crystal patterns)—A row of spots due to planes parallel to the axis of rotation or oscillation. Sometimes called zero line. Compare with layer-line, side spectrum.
- zone-axis** (in a crystal)—A line parallel to several crystal planes; the planes to which it is parallel form its zone

German Terms with English Equivalents

This list contains principally those German terms likely to be mistranslated. Many of the short words here given will usually be found in combination. Such combinations are only included if their proper translations cannot be derived from the translations for their parts. It must be understood that the translations given are to be preferred only when the term is used in its technical sense. In non-technical uses other equivalents will often be better.

- | | |
|---|---|
| Ablenkungswinkel—deviation | Lagerung—orientation. |
| Absorptionssprung—absorption-discontinuity | Leuchtschirm—fluorescent-screen. |
| Anregung—excitation | Loch—pinhole. |
| basisflächenzentriert—end-centered | Nebenspektrum—side-spectrum. |
| Basiszelle—unit cell. | Netzebene—lattice-plane. |
| Belichtung—exposure | Ordnung—order. |
| Beugung—diffraction | Punktgruppe—point-group. |
| Beugungsfigur—diffraction-pattern | Quelle—source. |
| Bezeichnung—indexing | Querrichtung—cross-direction. |
| Bild—image | Raumgruppe—space-group. |
| Blende—shield | regellos—chaotic. |
| Bremsstrahlung—heterochromatic X-radiation. | rhombsch—orthorhombic. |
| Brennfleck—focus. | Röntgenröhre—X-ray tube. |
| Deckoperation—covering-operation. | Röntgenstrahlen—X-rays. |
| dichteste Kugelpackung—close-packing of spheres. | Röntgenstrahlung—X-radiation. |
| Drehachse—rotation-axis. | Rückstrahl—back reflection |
| Drehkristall—revolving-crystal. | Schichtlinie—layer-line. |
| Drehspiegelung—rotatory-reflection. | Schneide—wedge. |
| Eigenstrahlung—characteristic X-rays. | Schraubachse—screw-axis. |
| Elementarzelle—unit cell. | Schraubung—screw-rotation. |
| Erregung—excitation. | Spalt—slit. |
| Faser—fiber. | Spiegelebene—reflection-plane. |
| Faserstruktur—fibering. | Spiralfaserstruktur—helical fibering. |
| Feinstruktur—fine structure, as may be revealed by diffraction. | Symmetriezentrum—inversion-center. |
| Fläche—face. | Textur—texture, especially orientation texture (preferred orientation) in crystalline aggregates. |
| Gitter—lattice. | Wälzrichtung—rolling-direction. |
| Gleitspiegelung—glide-reflection. | Würfel—cube. |
| Grobstruktur—coarse structure, as may be revealed by radiography. | Zähligkeit—multiplicity. |
| Häufigkeitsfaktor—frequency-factor. | Zerstreuung—scattering. |
| Hauptspektrum—principal spectrum. | |

Tool Steel Trade Names

The manufacturer's and the trade names of tool steels with the approximate composition of the important alloying elements are given in the following compilation. The firms are arranged alphabetically and then numbered.

If the trade name is known but not the manufacturer, this can be ascertained by referring to the second section which gives the trade names alphabetically arranged and each name preceded by the firm's number which corresponds with the listing in the first section.

Manufacturers are indicated by the superior ^a, the dealers by ^b, and importers by ^c.

	C	Mn	Cr	W	Mo				
1. Achorn Steel Co., ^{b, c} Boston									
Achorn Fagersta Best	1.05-1.15	0.20-0.25							
Achorn Fagersta Extra	1.00-1.10	0.20-0.25							
Achorn Fagersta Standard	0.90-1.00	0.25-0.30							
Achorn Fagersta Silver Die	1.00	0.20-0.30							
Achorn Fagersta Cold Heading	0.95-1.00	0.25-0.30							
Achorn Fagersta Extra Cutlery	1.07-1.12	0.20-0.25							
Achorn Fagersta Standard Cutlery	0.85-0.95	0.30-0.40							
Achorn Fagersta Chisel	0.80-0.90	0.25-0.30							
Achorn Fagersta Envelope Die	1.05-1.15	0.35							
Achorn Fagersta Shoe Die	0.90-0.95	0.35							
Achorn Fagersta Solid Drill	0.80-0.90	0.30-0.35							
Achorn Fagersta Smooth Bor Hollow	0.75-0.80	0.25-0.30							
Achorn Kloster Rema	0.02-0.05	0.02-0.07							
Achorn Fagersta Special Alloy Die	0.45-0.55	0.20-0.30	0.85-0.95	1-1.25	0.15-0.20				
Achorn Fagersta Finishing	1.15	0.40	0.40	2.50					
Achorn Fagersta Hot Die	0.55	0.45		5.00		Ni 3			
Achorn Fagersta Unbreakable Chisel	0.40-0.45	0.20-0.30	0.85-0.95	1-1.25	0.15-0.20				
Achorn Fagersta White Gold	1.15	0.40	0.40	1.25					
Achorn Fagersta Superior Oil	1.00	1.00	0.40	0.40					
Achorn Kloster Brilliant AX	0.70		4.00	18		V 0.75			
Achorn Kloster Prior Extra	0.60-0.70		4.50-5.00	18-19		V 1.25 Co 1			
Achorn Kloster Brilliant WKE	0.70 ^a	1.00	4.50	18		V 1.50 Co 5			
Achorn Fagersta High Production	1.55-1.70	0.70-0.90	11.50-12.50			V 0.15-0.25			
1a. Allegheny-Ludlum Steel Corp. ^a									
	C	Mn	Cr	W	Mo				
2. Amalgamated Steel Co., ^{a, b} Cleveland									
Malga			not available						
Creston	0.58	0.25	1.20	1.90		V 0.35			
Kromal	0.55	1.00	0.80		0.20				
Malgaloy			not available						
Malax	0.70		4.25	19.00	1.00	V 1 Co 5			
Dymal	1.65	0.25	11.50		0.90	V 0.35			
Thermal	0.58		3.40	14.50		V 0.60			
3. Anchor Drawn Steel Co., ^a Latrobe, Pa.									
Red Anchor Drill Rod.....	0.95-1.10	0.15-0.40	0.10			Ni 0.16			
Blue Anchor Drill Rod.....	1.20-1.35	0.15-0.40	0.10			Ni 0.10			
Carbon Vanadium Drill Rod	0.90-1.10	0.10-0.30				V 0.15-0.25			
Gold Anchor Drill Rod.....	0.68-0.73		3.75-4.25	17.5-18.5		V 0.95-1.15			
4. Atlantic Steel Co., ^b New York									
Atlantic No. 33.....	0.33	0.75	0.75		{ Si 0.75 Mo 0.75	Cu 0.75			
Atlantic 44.....	0.44	0.75	0.75		{ Si 0.75 Mo 0.75	Cu 0.75			
Atasco Special.....	0.80-1.00	0.50-1.00			0.30				
Atlantic Die Steel.....	0.55-0.65		90-1.00			Ni 1.50- 1.70			
A-O-T H.S. Steel.....	0.65			17-18	0.60-0.80	Co 9.50-10.50			
Atl. H.S. Steel.....	0.60-0.70		4.00	18		V 1.25- 1.50 V 1.00			
	C	Mn	Cr	W	Mo	Si	Ni	V	Co
5. Bethlehem Steel Co., ^a Bethlehem, Pa.									
Bearing (Standard).....		1.00	0.30	1.40		0.25			
Bearing (H. T. W.)		0.90	0.40	1.75		0.25		0.20	
Bearing (Cr-Mo).....		1.05	0.30	1.15		0.20			
Best		x	0.30			0.20		0.20	
Broaching		0.80	0.20			0.20			
Cellini		0.95	0.30			0.70		0.25	
Channeller		0.80	0.20			0.15			
Cobadux "A"		0.90	0.45	5.00	4.00	0.30			37.00

* See Ludlum Steel Co.

(Continued)

5. Bethlehem Steel Co.,^a Bethlehem, Pa.—Continued

	C	Mn	Cr	W	Mo	Si	Ni	V	Co
Cobadux "B".....	0.80	0.45	4.50	9.00		0.30			19.00
Collet	0.85	0.70				0.25		0.20	
Comokut High Speed.....	0.73	0.30	4.50	18.25	0.75	0.50		1.25	5.00
Extra Special High Speed.....	0.70	0.25	4.25	14.00		0.40		2.25	
57 Hot Work.....	x	0.30	2.75	9.00		0.30		0.50	
57 Hot Work (Special).....	x	0.30	2.75	12.50		0.30		0.50	
445 Hot Work.....	0.85	0.30	3.75			0.25			
Finishing	1.30	0.30		4.00	0.40	0.40			
H. V. High Speed.....	0.80	0.30	4.50	18.50	0.60	0.25		2.15	
Lehigh Die and Tool, "H" Temper.....	1.65	0.35	12.00		0.80	0.30		0.30	
Lehigh Die and Tool, "L" Temper.....	0.85	0.25	11.50		0.45	0.30	0.95	0.30	
H. M. High Speed.....	x	0.20	3.75	1.55	8.75	0.35		1.10	
Nail Die.....	1.15	0.30				0.35			
Omega.....	0.55	0.70			0.45	2.15		0.20	
Permanent Magnet No. 1.....	0.65	0.30		6.00		0.20			
Permanent Magnet No. 2.....	0.90	0.30	3.75			0.20			
Piston	1.15	0.30	0.55			0.20		0.20	
6 Nickel.....	0.20	1.05				0.25	35		
7 Nickel.....	0.25	0.90				0.20	42		
65% Nickel—15% Chromium.....	0.08	2.25	14.00			0.35	62		
67 Chisel.....	0.45	0.25	1.25	2.15		0.20		0.20	
67 Tap.....	1.20	0.25	0.75	1.50		0.20		6.20	
71 Alloy.....	0.65	0.80				2.00			
Special High Speed.....	x	0.25	4.00	18.00		0.25		1.00	
Superior	x	0.25				0.20		0.20	
Tool Room Oil Hardening.....	0.90	1.15	0.50	0.50		0.25		0.20	
Tough, "H" Temper.....	0.70	0.20	0.80			0.25		0.20	
Tough, "M" Temper.....	0.50	0.65	0.95			0.25		0.20	
Tough, "S" Temper.....	0.50	0.30	1.30			0.20		0.20	
Tong Rein.....	x	0.30				0.20			
X, XCL, XX, XXX.....	x	0.30				0.20			

x—As specified or needed for a particular purpose.

	C	Mn	Cr	W	Mo	Si		
6. Boyd-Wagner, ^b Chicago								
Rekord Superior.....	0.70	0.30	4.00	18.00		0.20	Co	0.30
Rekord Extra.....	0.80	0.30	5.00	18.50	1.50	0.20	V	1.50
							Co	2.20
Rekord Select.....	0.80	0.30	5.00	18.50		0.20	V	1.50
							Co	5.50
Rekord Eminent.....	0.75	0.30	5.00	18.50		0.20	V	1.50
							Co	10.00
E. Z. 14 W Hot Die.....	0.45	0.30	3.00	14.00		0.20	V	0.20
E. Z. 9 W Hot Die.....	0.30	0.30	3.00	9.00		0.20	V	0.20
Extra Fraz.....	2.20	0.60		1.00		0.40	Co	1.00
							Ni	0.50
Hypno No. 62.....	2.00	0.60	12.00			0.40		
Crown W Fast Finishing.....	1.30	0.30	1.80	4.00		0.20	V	0.20
Special No. 18 S.....	0.45	0.30	1.40	2.20	0.30	1.00	V	0.20
Arrow Oil Hardening.....	0.95	1.20	0.50	0.50		0.20	V	0.10
Hy-Lo Oil Hardening.....	0.85	2.25	0.04			0.30	V	0.10
Bowco Oil Hardening Tubing.....	1.00	0.50	1.50			0.20		
Bowco Water Hardening Tubing.....	0.90	0.30	1.00			0.20		
Impress	0.50	0.30	1.50	2.00		0.20	V	0.20
Die Cast.....	0.45	0.40	1.40	2.30		0.25	V	0.20
Moldie	0.80	2.00	0.10			0.30	V	0.10
Very Best.....	1.05	0.30	0.50			0.20	V	0.10
Best Carbon.....	1.06	0.30				0.20	V	0.05
No. 4.....	0.90	0.30				0.20		
Standard	1.10	0.30				0.20		
No. 41.....	1.10	0.60				0.20		
B.W. Point 5.....	0.02	0.18						
B.M.S. Plate.....	0.15	0.30						

	C	Mn	Cr	W	Mo	Si	V
7. Braeburn Alloy Steel Corp., ^a Braeburn, Pa.							
Bonded Carbide..	0.65-0.70	0.15-0.30	4.25-4.75	17.50-18.50	0.60-0.80	0.15-0.30	2.00-2.25
							Co 9.50-10.50
Twinvan	0.78-0.84	0.25-0.35	4.00-4.50	18.00-19.00	0.50-0.80	0.20-0.50	2.00-2.25
Cobalt	0.65-0.73	0.15-0.30	3.75-4.25	17.50-18.50	0.75-1.00	0.15-0.30	0.85-1.00
							Co 4-4.50
Vinco	0.50-0.75	0.15-0.30	3.75-4.25	17.50-18.50		0.15-0.30	0.95-1.05
T-Alloy	0.30-0.35	0.15-0.30	3.00-3.50	10.00-11.50	0.15-0.30	0.20-0.35	0.30-0.50
Mo-Out	0.60-0.85	0.30 max.	3.50-4.00	1.20-1.80	8.20-9.20	0.20-0.45	0.90-1.30
Superior No. 1...	2.05-2.20	0.40-0.60	11.50-13.50			0.20-0.40	0.55-0.65
Superior No. 3...	1.40-1.60	0.20-0.40	11.00-13.00		0.70-0.90	0.20-0.40	0.75-1.00

(Continued)

	C	Mn	Cr	W	Mo	Si	V
7. Braeburn Alloy Steel Corp.,^a Braeburn, Pa.							
—Continued							
Kiski	0.90-1.00	1.00-1.20	0.43-0.57	0.45-0.70		0.30-0.45	0.15-0.25
Hot Die No. 2....	0.90-1.05	0.20-0.40	3.90-4.30			0.25-0.40	
Vibro	0.50	0.20-0.30	1.30-1.50	1.75-2.00		0.15-0.30	0.20-0.30
Special	0.60-1.40	0.20-0.35				0.10-0.25	0.15-0.25
Extra	0.60-1.40	0.20-0.35				0.10-0.25	
Standard	0.60-1.40	0.20-0.35				0.10-0.25	
Chrome Vanadium	0.46-0.85	0.35-0.50	0.60-0.80			0.10-0.35	0.15-0.20
R. B. Special....	0.45-0.50	0.70-0.80	0.75-0.85			0.50-0.60	
Die Casting.....	0.40-0.50	0.50-0.70	2.40-2.65			0.20-0.35	0.20-0.30
Pressurdie No. 1..	0.30-0.40	0.20-0.35	4.75-5.50	4.75-5.50	0.15-0.25	0.80-1.00	0.15-0.25
							Co 0.40-0.60
Pressurdie No. 3..	0.32-0.37	0.55-0.65	4.90-5.25		0.45-0.60	0.85-1.00	0.10-0.15
Viking	1.00-1.10	0.30-0.50	1.00-1.10		0.35-0.50	0.20-0.35	
Z. N.....	0.45-0.50	0.60-0.80	0.80-0.90			0.15-0.30	
	C	Mn	Cr	W	Mo	Si	V
8. Canadian Atlas Steels, Ltd.,^a Welland, Ont.							
Canada							
Atlas Refined (Reg. C)....			0.80-1.10				
Atlas Extra (Ex. C).....			0.95-1.25				
Atlas Double Extra (Sp. C).....			0.90-1.10				
Atlas Special Alloy (Va).....			0.80-1.10				0.15 min.
Atlas "Q" (Cr).....			1.20		0.50		
Atlas Triple Extra (W) (Fin.).....			1.35			3.75	
Monark (Shock Resisting).....			0.60	0.75	0.30	0.20	Si 2
Falcon (Cr, W).....			0.50		1.25	2.00	0.20
Badger (Cr, W).....			1.25		0.40	1.50	0.20
E. B. Alloy (Cr, Hot Work).....			0.85		3.75		0.20
Ultimo No. 6 (Cr, Ni).....			0.55		0.75	0.75	Ni 1.60
Hot Die (Cr, W, Va).....			0.35		3.25	11.00	0.40
Keewatin (Mn).....			0.90		0.50	0.50	
N N (Cr).....			2.25	1.15			0.25
F N S (Cr).....			1.50	12.00		0.80	0.25
Spartan			0.50-0.75		4.00	18.00	1.00
Trojan (W, Cr, Mo, Va).....			0.80		4.00	18.00	2.00
Nipigon (Co).....			0.75		4.00	18.00	2.00
							Co 7
	C	Mn	Cr	W	V	Si	
9. Cannon-Stein Steel Corp.,^b Syracuse, N. Y.							
	As						
Rita Standard	Desired	0.40 max.				0.20	
Rita Electric	0.80-0.90	0.30 max.				0.10-0.25	
	As						
Rita Extra	Desired	0.40 max.				0.20	
Rita Standard Drill Rod	1.00-1.10	0.25-0.40				0.10-0.25	
Rita Special Drill Rod	1.25-1.35	0.20-0.25				0.15-0.30	
	As						
Rita Special Tool	Desired	0.20-0.30			0.15-0.20	0.15-0.30	
Rita Extra Special	1.40	0.20-0.30	0.15	4.00	0.30	0.15-0.30	
Rita Chrome-Vanadium C.V.K.	0.75		0.90			0.20	
Rita T.C.V. Alloy (W) ..	0.45-0.55	0.20-0.30	1.35	2.28	0.25	0.20-0.30	
	As						
Rita Car-Van Die (C, V)	Desired	0.20-0.30	0.10 max.		0.20	0.15-0.30	
Rita Hot Forging Die							
No. 1 (W)	0.30	0.20-0.35	4.00	15.00	0.50	0.30 max.	
Rita Hot Forging Die							
No. 2 (W)	0.45	0.20-0.35	2.75	15.00	0.50	0.50 max.	
Rita Carbon Vanadium							
Drill Rod (V)	0.95	0.35	0.95		0.15-0.18		
Rita Carbon-Vanadium							
Drill Rod	0.50	0.65	0.95		0.15-0.18		
Rita High Speed (W) ..	0.68	0.20	4.00	18.00	1.00	0.30	
Rita 3-Point Die-Hi-							
Carbon Hi-Chrome ..	2.25	0.55	13.00			0.30-0.35 Ni 50	
Rita No-change Oil							
Hardening (Mn)	0.95	1.50-1.75	0.15-0.25			0.30	
Rita Oil Hardening							
Drill Rod	0.95	1.50-1.75	0.15-0.25			0.30	
Rita Cobalt High Speed	0.70	0.20	4.00	17.25	1.00	0.32 Co 4.50	
"Rita" Composite Die ..	1.00	0.30				0.20 Co 5-10	
						Iron Portion	

(Continued)

10. Carboloy Co., Inc.,^a Detroit

Carboloy (Cemented Carbides & Tungsten Cobalt Alloys)

	C	Mn	Cr	W	V	Si	Mo
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11. Carpenter Steel Co.,^a

Reading, Pa.

Comet (Reg. C) ...	1.10						
Extra (Ex. C) ...	1.10						
Special (Sp. C) ...	1.10						
Solar	0.50	0.40				1.00	0.50
Excelo	0.55	0.40	1.50	2.50	0.35	0.30	
K-W	1.3			3.5			
T-K (Hot Work) ..	0.5		3.0	8.0			
Gold Star	0.72		3.75	12.5	2.1		Co 3.75
Star Zenith	0.70		3.75	18.5	1.1		
Stentor (Mn)	0.90	1.60					
Hampden	2.1	12.5					Ni 0.50
610 Air Hardening ..	1.5	0.8	12		0.20		
R.D.S.	0.75	0.3	1.0			0.25	Ni 1.75
D Y. O.	0.3	0.3	4	14.5	0.5	0.25	
Carpenter Moly ...	0.78		3.75	1.50	1.15		8.50

	C	Mn	Cr	W	V	Mo
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12. Colonial Steel Div.,Vanadium Alloy Steel Co.,^a Pittsburgh

Vascoloy-Ramet (Cemented Carbide)							
Red Cut Superior (W, Cr, V).....	0.56-0.75		4.00	18.00	1.05		
CoCo Turning (Co).....	0.72		4.00	18.00	1.00		Co 4.50
Colonial No. 3 (Hot Work) (W) ..	0.33		3.50	9.50	0.45		
Colonial No. 4 (Fin.) (W).....	1.30			3.50			
Ohio Die (Cr).....	1.55		12.00		0.85	0.80	Co 0.40
Colonial No. 6 (Mn).....	0.95	1.30	0.50	0.50	0.15		
Colonial No. 7 (V).....	0.60-1.40				0.18		
Red Star Tungsten (W).....	1.20		0.45	1.60	0.20		
Tungo (W).....	0.50		1.65	2.00	0.25		
Silman (Si Mn).....	0.55	0.85	0.25		0.30		Si 2.10
Colonial No. 35 (Hot Work) (Cr) ..	0.95		4.00				
Colonial No. 14	0.60-1.30						
Red Star Tool.....	0.60-1.30						

	C	Mn	Cr	W	V	Mo
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13. Columbia Tool Steel Company,^a ChicagoHeights, Ill.^a

Clarite High Speed			4.00	18.00	1.25		
Vanite High Speed			4.00	18.00	2.00	0.65	
Maxite Super High Speed ..			4.00	14.00	2.00	0.60	Co 4
Formite (Hot Work).....	0.40		3.75	14.50	0.65		
Columbia Double Special (Fin.) ..	1.30		0.55	3.25			
Superdie (High C, Cr).....	2.20		10.50	1.00			
Special Wire Drawing Alloy	2.30		1.85	10.50			
Silvanite	1.25		4.00	8.00			
Self Hardening	1.60		3.75	9.50			
Oldie (Non-Deforming).....	0.90		1.60	0.50			
Exl-Die (Non-Deforming).....	0.90	1.15	0.50	0.50			
Tapdie	1.25		0.20	1.00			
Cutter Alloy.....	1.05		0.25	0.25			
Phoenix (Heat Resisting) ..	0.95		3.95				
Buster (Shock Resisting).....	0.50		1.20	2.25	0.25		
Artie	0.95		0.30		0.02		
Columbia Special (Sp. C).....	Any		0.18		0.02		
Columbia Extra Vanadium.....	Any				0.20		
Columbia Extra	Any						
Waterdie	1.00		0.50				
Waterdie B.....	1.00		0.50				
Columbia Standard Vanadium.....	Any				0.20		
Columbia Standard	Any						
Airex	0.55	0.75					Si 2
Columbia Electrex	Any						

	C	Mn	Cr	W	Mo	V	Si
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14. Craine-Schrage Steel Co.,^{b, c}

Detroit

Crasco Green Label.....	0.95-1.05	0.15-0.35					.15-.35
Crasco White Label.....	1.00-1.10	0.15-0.35					.15-.35
Crasco Drill Rod.....	1.00-1.10	0.15-0.35					.15-.35

^aThese steels are also carried by the Pratt & Inman Co., Worcester, Mass.

(Continued)

	C	Mn	Cr	W	Mo	V	Si
14. Craine-Schrage Steel Co.,^{b, c} Detroit—Continued							
Crasco Red Label (Mn, W, Cr)	0.85-0.95	1.00-1.25	0.40-0.66	0.40-0.60			.25-.35
Crasco Black Label (Cr)	1.40-1.60	0.25-0.35	0.11-0.13		0.70-0.90	0.15-0.25	.25-.35
Crasco Special Vanadium	0.95-1.05	0.15-0.35				0.15-0.25	.15-.35
Crasco High Speed.....	0.65		4.00	18.00		1.00-2.00	
Crasco Tool Bits.....	0.65		4.00	18.00		1.00	
Crasco Finishing	1.35-1.45	0.15-0.35		3.75-4.25		0.15-0.25	.40-.50

	C	Mn	Cr	W	Mo	V	Co	Si
15. Crucible Steel Co. of America,^a New York								
Rex AAA	As desired		4.00	18.00	0.50	1.00	5.00	
Rex AA	"		4.00	18.00		1.00		
Rex A	"		4.00	18.00				
Rex Supervan.....	0.80		4.00	18.00	0.65	2.00		
Rex Champion.....	0.75		4.00	14.00		2.00		
Rex 95	0.80		4.00	14.00	0.50	2.00	5.00	
Rex TMO	As desired		3.75	1.50	8.75	1.10		
Rex VM	0.86		4.00		8.00	2.00		
H.Y.C.C.	2.25		12.00			0.25		
Airdi	2.25		12.00		1.00	0.25		
C.C.A.	1.50		12.00		0.80	0.25		
La Belle No. 24.....	1.10		12.00		1.00	0.25		
Sanderson Double Special.....	1.30		0.25	3.60				
Crescent Double Special.....	1.30			3.60				
Wortle No. 1 Drawing Die.....	2.10		2.80	4.25				
Wortle No. 2 Drawing Die.....	1.85		1.90	4.25				
Wortle No. 3 Drawing Die.....	2.10			1.50				
Wortle No. 4 Drawing Die.....	1.95			3.00				
Wortle No. 5 Drawing Die.....	1.85	1.90	1.85	12.00				
Peerless A	0.30		3.25	9.00		0.25		
Peerless B	0.45		2.75	15.00		0.40		
Peerless C	0.30		2.75	15.00		0.40		
Peerless D	0.45		2.00	11.00		0.20		
Crescent Hot Work No. 2.....	0.95		3.75					
LaBelle No. 89 (Hot Work).....	0.55		4.00		0.50	1.00		
LaBelle Special Hot Die.....	0.40		2.25					Ni 2.50
LaBelle Cromonic (Hot Work)...	0.50	1.25	7.00		0.75			Ni 1.50
Pyro Die (Hot Die).....	0.40		1.00			0.25		
Atha Pneu (Hot Work).....	0.55		1.25	2.75		0.25		
Atha Pneu (Cold Work).....	0.45		1.25	2.75		0.25		
Paragon Oil Hardening	0.90	1.60						
Champion Non-Changeable	0.90	1.15	0.50	0.50				
LaBelle 2-70	0.60	0.80						2.00
LaBelle Silicon No. 2.....	0.60	0.80			0.30			1.90
Alva Special	0.75-1.20					0.25		
Alva Extra	0.75-1.20					0.25		
Champion Extra	0.75-1.20			1.25				
Crescent Special Alloy Chisel....	0.45		1.25	2.40				
Atha Rim Roll.....	1.00		0.50					
Crescent Rim Roll.....	1.00		0.50					
Atha Chrome Roll.....	0.90		1.35					
Sanderson Special	As desired							
Crescent Special	"							
Sanderson Extra	"							
Crescent Extra	"							
Sanderson Tool	"							
Crescent Tool	"							
Black Diamond Tool.....	"							
Granada Tool	"							

16. Cyclops Steel Co.*

	C	Mn	Cr	W	Mo	V	Co	Si
17. Darwin & Milner, Inc.,^{b, c} Cleve- land								
A-B-C (W, Cr).....	0.40	0.50	0.25	0.50			0.30	
Cannon (W, Cr, V).....	0.60		3.50	16.00		1.06		
Cannon-Special (High Speed)...	0.70		4.00	18.00	0.50	2.00		
Cobaltrom PRK-33	1.40	0.30	13.00		0.80		3.30	0.60
Darwin No. 1 (Air Hdg).....	1.40	0.30	13.00		0.80	0.30		0.26
Darwin 505 (High Speed).....	0.60	0.30	4.50	18.00	0.50	1.00	5.00	0.30
Darwin No. 1366 (High Speed).....	0.70	0.40	4.00	18.00	0.50	2.00	15.00	0.30
Firex (Cr, Ni).....	0.40		1.10					0.30
Firex-Special	0.40		1.50		0.80			Ni 4.50

*See Universal-Cyclops Steel Corp.

(Continued)

TOOL STEEL TRADE NAMES

23

	C	Mn	Cr	W	Mo	V	Co	Si
17. Darwin & Milner, Inc., Cleveland								
—Continued								
"H" (Die Steel).....	0.95	1.00	0.40					0.30
Ideor (Si, Cr, W).....	0.40	0.30	1.00	2.00				1.00
Neor (C, Cr).....	2.20	0.40	13.00					0.60
N-32 (Mn, Ni).....	0.40	0.60						0.30
S-I-W (Hot Work).....	0.40	0.30	3.10	10.00		0.25		Ni 3.50
								0.40

	C	Mn	Cr	W	Mo	V	Co	Si
18. Delaware Tool Steel Corp.,^{b,c} Wilmington, Del.								
National			0.70		4.00	18		1.25
P-D Tungsten (Hot Work) (W, Cr, V)....			0.50		3.25	9.5		0.25
Cartun (Fin.) (W, Cr).....			1.35			2.75		
C-4 (Hot Die) (Cr, V).....			0.95		4.00			
HC-HC (Cr).....			1.85		12.25			
Pennant (Mn, V).....			0.90	1.60				0.20
Delasteel Alloy			0.50	0.35			0.55	0.25
Delaware Extra			0.60-1.50					
Delaware Standard			0.60-1.10					
Drillalloy			0.65	0.70			0.40	
Molel Alloy			0.50		0.75		0.40	0.50

	C	Mn	Cr	W	Mo	V	Co	Si
19. Detroit Alloy Steel Co.,^b Detroit								
Krokoloy (Cr, Co)	1.40-1.60		12.00-14.00		8-9		3.0-3.5	.50-.60
Martin Steel (Co, Cr, Mo)	1.40-1.60		12.00-14.00		1.10-1.25	.35-.40	1.10-1.25	
Castaloy (Cr, Mo)	1.40-1.60	0.45-0.55	12.00-14.00		.7-.8		.7-.8	
Carbomang (C, Mn)	0.90-1.00	1.0-1.25	0.45-0.60	.40-.60				

	C	Mn	Cr	W	Mo	V	Co	Si	Ni
20. Henry Disston & Sons,^a Inc., Philadelphia									
Best (Sp. C)	As ordered		0.25						0.20
Extra (Ex. C)	As ordered		0.25						0.20
Standard (Reg. C).....			0.25						0.25
D-1	1.05		0.25						0.25
Celero	1.35		0.25	0.25	2.75				0.20
Keystone Alloy Chisel.....	0.50		0.30	1.10	1.95		0.25		0.20
							max.		
812 Die Steel.....	1.75-1.85		0.30	12.25					0.25
Kutkwik	As ordered		0.25	4.00	18.00		1.00		0.25
D-6-Co	0.80		0.30	4.00	19.25	0.90	2.00	6.00	0.20
Mansil Oil Hardening.....	0.90		1.15	0.50	0.50				0.35
Croloy	1.50		0.30	12.00		0.80	1.00		0.30
D-29	0.58		0.74	0.12		0.49	0.15		1.35
				max.			max.		
Nivan	1.10		0.30	.40			0.25		0.25
							max.		1.40
Polaris	As ordered		0.30		0.20				0.25
					max.				0.70
D-9 Va	"		0.55				0.25		0.50
							max.		
VaTool Best									
" Standard	"		0.25				0.25		0.15
" Extra									
Nicroman	0.65		0.40	1.00					0.20
H.R.W.	0.95		0.25	3.75			0.20		0.30
							max.		1.65
Semi High Speed.. ..	1.10		0.25	0.30	1.15		0.25		0.15
							max.		

21. Edgcomb Steel Company, Philadelphia^a.

	C	Mn	Cr	W	Mo	V	Co
22. Elbert Steel Corp.,^b New York							
Elberts High Speed.....	0.72		4.00	18		1.00	
Elberts Elbit Molybd. High Speed.....	0.81		4.25		9.00	2.20	
Elberts C-T High Speed	0.80		4.25	20.50	0.60	1.30	12.25

*Same trade names as Allegheny-Ludlum.

(Continued)

TOOL STEEL TRADE NAMES

	C	Mn	Cr	W	Mo	V	Co	
22. Elbert Steel Corp.,^b New York--Continued								
Elbert's Hi-Chrome Die Steel.....	2.20		12.00			0.80	0.50	
Elberts Air Cool Die Steel.....	1.55		12.00		0.80	0.85	0.40	
Elberts EZ Oil Hardening Steel ..	0.95	1.30	0.50	0.50		0.10		
Elberts Tool Steel	1.00	0.20						Si 0.20
Elberts C-Van	1.00	0.20				0.15		Si 0.20
Elberts HW Hot Work Steel	0.33		3.50	9.25		0.45		
Elberts Hot Tool.....	0.32		4.75	0.75	1.00			
Elberts Grip Die.....	0.98	0.35	3.90					Si 0.35
Elberts TCV Alloy Chisel Steel. .	0.50		1.65	2.00		0.25		

	C	Mn	Cr	W	Mo	Si	Ni	V	Co
23. Engelsted, K.,^c New York									
1	0.60	0.30				0.20			
2	0.70	0.30				0.20			
3	0.80	0.30				0.20			
3½	0.90	0.30				0.20			
4	1.00	0.30				0.20			
5	1.10	0.30				0.20			
6	1.20	0.30				0.20			
7	1.30	0.30				0.20			
8	1.45	0.30				0.20			
9B	0.60-1.45	0.30	0.15			0.20			
9A	0.60-1.45	0.30	0.25			0.20			
9	0.60-1.45	0.30	0.45			0.20			
10	0.60-1.45	0.30	1.00			0.20			
11	0.60-1.45	0.30	1.50			0.20			
12	0.80	0.30	0.45			0.20		0.10	
13	0.95	0.30	0.45			0.20		0.10	
14	1.05	0.30	0.45			0.20		0.10	
16	0.95	1.25	0.50	0.50		0.20		0.10	
17	1.15	0.30		1.00		0.20			
18	0.45	0.30	1.40	2.20	0.30	0.25		0.20	
19	1.15	0.40	0.50	1.50		0.10			
20	1.30		1.80	4.00				0.20	
21	1.30		0.50	5.00					
22	0.45		3.00	9.00					
23	0.45		3.00	14.00					
25	0.70		4.00	18.00				1.00	
26	0.80		5.50	18	1.50			1.50	2.00
27	0.80		5.50	18	1.50			1.50	5.50
28	0.75		5.50	18	1.00			1.50	10.00
41	0.50-1.30	0.55				0.20			
42	0.45-0.70	0.90				0.70			
43	0.60	0.90				1.90			
61	2.20		13.00						
62	2.20		12.50						
85	0.50	0.60	0.80		0.20	0.30	3.25		

	C	Mn	Cr	W	Mo	Si	Ni	V	Co
24. Faltoute Iron & Steel Co.,^b Newark									
Red Cut Superior	0.50-0.75	0.20	4.00	18.00		0.32		1.00	
E.V.M.	0.82	0.25	4.25	18.50	0.65	0.35		2.10	
Red Cut Cobalt.	0.72	0.20	4.00	17.25	0.50	0.32		1.00	4.50
Gray Cut Cobalt.	0.80	0.20	4.25	20.50	0.60	0.30		1.30	12.25
Crocar	2.20	0.20	12.00			0.30		0.80	0.50
Ohio Die	1.55	0.20	12.00		0.80	0.35		0.85	0.40
Vanadium Type D	0.50	0.20	0.80			0.25		0.20	
Vanadium Type G	0.60	0.20	0.80			0.25		0.20	
Vanadium Type H	0.70	0.20	0.80			0.25		0.20	
Vanadium Type K	0.80	0.20	0.80			0.25		0.20	
Vanadium Type N	0.92	0.20	0.80			0.25		0.20	
Vanadium Type BB	1.00	0.20	0.80			0.25		0.20	
Colonial #8	0.95	1.30	0.50	0.50		0.22		0.10	
Red Star Tungsten.....	As								
Hotform	Temper	0.25	0.42	1.60		0.30		0.20	
Par-Exc	0.32	0.30	4.75	0.75	1.00	0.90			
Colonial #14	0.50	0.20	1.65	2.00		0.28		0.25	
Red Star	0.90	0.25				0.20			
Ideal	Varies								
	Varies								

	C	Mn	Cr	W	Mo	Ni	Co	V
25. A. Finkl & Sons Co.,^a Chicago								
Durodi (Cr, Ni, Mo)	0.50-0.70	0.45-0.65	0.75-1.00		0.60-0.90	1.25-2.00		
FX (Cr, Ni, Mo)	0.50-0.70	0.45-0.65	0.50-1.00		0.15-0.35	1.25-2.00		
FS (Cr, Ni, Mo)	0.50-0.70	0.45-0.65	0.50-1.00		0.15-0.35	1.25-2.00		
FM (Cr, Mo)	0.50-0.70	0.50-0.90	0.75-1.00		0.15-0.25			
Cold-Hot (Cr, Ni, Mo).....	0.70-0.90	0.20-0.50	0.40-0.80		0.15-0.25	0.50 max.		

(Continued)

	C	Mn	Cr	W	Mo	Ni	Co	V
26. Firth-Sterling Steel Co.,^a McKeesport, Pa.								
Circle C	0.77		4.50	18.50	1.00		9.00	1.75
Blue Chip	0.72		4.00	18.00				1.00
H V. Blue Chip	0.81		4.50	18.50	0.75			2.20
XDM Steel	0.45		4.00	18.00				0.50
Cromovan	1.80		12.00		0.80			1.00
Triple Die Steel	2.25		12.50					0.20
J. S. Punch & Chisel Steel.....	0.50	0.30	1.40	2.25				
C. Y. W. Choice (Hot Work)	1.00	0.50	3.50					
Invario Oil-Hardening	0.90	1.15	0.50	0.50				
R. T. Steel (Fast Finishing).....	1.30	0.40	0.25	3.50				
Special A S.V. (Sp.C).....	Varies							
Special (Sp.C)	Varies							
Diamond "M" (Sp.C).....	Varies							
Best (Sp.C)	Varies							
Extra (Extra C)	Varies							
Sterling XX	Varies							
Sterling "V"	Varies							
Sterling (Reg.C)	Varies							
Silver Star	Varies							
H. M. Blue Chip.....	Not Available							
L. C. Blue Chip.....	Not Available							
X. D. H. Steel.....	Not Available							
X. D. L. Steel.....	Not Available							
L. T. Forging Steel.....	Not Available							
Sterling Nitrad No. 1	Not Available							
Meteor	Not Available							
Chimo	Not Available							
Double Special ..	Not Available							

C

27. D. C. Gautier & Co.,^b New York

Standard G ..	0.80-0.90
Extra G ..	0.90-1.05
Special G ..	0.80-0.90
Standard G Chisel ..	0.70-0.85

	C	Mn	Cr	W	Mo	Si	Ni	V
28. Great Western Steel Co., Inc.,^{b, c} Los Angeles								
Fagersta Standard	1.00	0.35				0.15		
Fagersta Special	1.00	0.35				0.15		
Fagersta Hollow Drill ..	0.80	0.30				0.10		
Fagersta "30" Drill ..	1.00	0.30	1.10		0.35	0.30		
Fagersta Header Die	1.05	0.35				0.20		0.50
Fagersta Oil Hardening ..	0.95	1.05	0.45	0.45				
Fagersta High Production ..	1.80	0.30	12.00		0.80	0.30		0.20
Fagersta Piercer	0.80	0.40		5.00		0.27	3.00	
Fagersta Rock Drill Piston....	0.95	0.20				0.15		0.25
Fagersta Hot Work	0.30	0.30	3.50	9.00		0.45		0.40
MiRyCal Chisel	0.45	0.25	0.90	1.00	0.20	0.20		
Polhem Drawing Die	1.80	2.00	2.00	13.00				
Dannemora A D 95 Coining Die	0.70		0.25	1.00				0.15

	C	Mn	Cr	W	Mo	V	Co	Si
29. Halcomb Steel Div., Crucible Steel Co. of America,^a Syracuse, N. Y.								
Special	As Desired							
Extra Special	As Desired							
Extra Warranted	As Desired							
Standard	As Desired							
Ketos ...	0.90	1.25	0.50	0.50				
Krovan ..	0.90		1.00			0.20		
Liberty ..	1.20		0.30	1.25				
Special Vanadium	As Desired					0.20		
Peerless Cold Header Die.....	0.95	0.25						0.25
Halcut	0.45		1.25	2.60				0.20
Krosil Chisel Steel.....	0.50	0.90			0.35			1.50

(Continued)

	C	Mn	Cr	W	Mo	V	Co	Si
29. Halcomb Steel Div., Crucible Steel Co. of America, Syracuse, N. Y.—Continued								
Haldi	2.25		12.00		0.90	0.20		
Marathon	2.25		12.00		0.90	0.20		
Air Hardening	1.80	0.35	4.00		4.10			0.65
Double Special	As Desired	0.30	0.25	3.50				0.45
O.C.S. Die Casting	0.35	0.35	5.25	4.25		0.40		1.15
NuDie Casting	0.38	0.40	5.00		1.40	0.40		1.00
Thermo Die	0.40	0.65	2.40			0.20		0.25
Pyro (Hot Die)	0.45	0.70	0.85			0.20		0.25
L. C. T. Alloy (Hot Work)	0.45		3.00	15.00		0.40		
L. C. T. #2 (Hot Work)	0.40		3.00	11.50		0.40		
L.L.C.T. (Hot Work)	0.25		4.00	15.00		0.40		
Halcomb Hot Work	0.40		3.50	8.75	0.25			
Wortle #4 Drawing Die	1.95	0.45	3.00					0.15
Dreadnought High Speed	As Desired		4.00	18.00		1.15		
Supervan Dreadnought High Speed	0.80		4.25	18.50	0.75	2.10		
Super Dreadnought High Speed	0.75		3.75	14.00		1.85		
Halcomb 999 High Speed	0.80		3.75	14.00	0.55	1.80	5.35	
VM Dreadnought High Speed	0.86		4.00		8.00	2.00		
	C	Mn	Cr	V	Si	Co	W	
30. Hawkrige Brothers* Co.,^b Boston								
Hawk Brand	0.60-1.40	0.15-0.30				0.15-0.30		
Hawk Impacto	0.90-1.10	0.30-0.40				0.40-0.50		
Hawk Special	0.90-1.40	0.15-0.30	0.20-0.30			0.40-0.60		
Hawk Vanadium	0.70-1.40	0.15-0.30			0.15-0.25	0.15-0.30		
Hawk H (Cr, V)	0.85-1.10	0.30-0.60	1.00-1.50			0.15-0.30		
	C	Mn	Cr	V	Si	Co	W	
31. Haynes Stellite Co.,^a Kokomo, Ind.								
Haynes Stellite J-Metal			30-35			45-55	12-17	
	C	Mn	Cr	W	Mo	V		
32. Heller Brothers Co.,^a Newark, N. J.								
Purple Label	0.50-1.10	0.20-0.90						
Electric Brand White Label	0.75-0.90							
Green Label	0.80-1.10							
Blue Label	0.80-1.10							
Yellow Label (V)	0.80-1.10						0.15-0.25	
Orange Label Chisel (Cr, W, V)	0.45-0.55		1.25-1.75	2-3			0.20-0.30	
Gray Label (Mn, W)	0.80-0.90	1.20-1.40		0.30-0.50				
Brown Label (Cr)	0.85-1.00		3.00-4.00					
Red Label Peerless (W, Cr, V)	0.60-0.70		3.00-4.00	18-20			1.20-1.50	
Die L (Cr, Mo)	1.40-1.60	0.20-0.40	11-13		0.70-0.90		1.25-1.50	
Cold Label Peerless (W, Co, Cr, V)	0.60-0.70		3.00-4.00	18-20				Co 2-3
70-20 M (Mo)	0.60-0.70				0.15-0.25			
	C	Mn	Cr	W	Si	V		
33. Houghton & Richards,^b Inc., Boston								
Yellow Label	1.30-1.40	0.25-0.30			0.20-0.25			
Grey Label	0.90-1.00	0.20-0.25			0.20-0.25			
Silver Label	1.30-1.40	0.25-0.30			0.20-0.25			
Purple Label	1.05-1.15	0.22-0.25			0.20-0.25			
Red Label	1.10-1.20	0.20-0.25			0.20-0.25			
Blue Label	0.80-0.90	0.25-0.30			0.20-0.25			
Rose Label	1.10-1.20	0.20-0.25			0.20-0.25			
Brown Label	0.90-1.05	0.20-0.25			0.20-0.25			
Extra M G	0.90-1.00	0.85-1.00	0.50-0.60		0.20			
Special K	2.25-2.40	0.25-0.40	12.75-13.25		0.15-0.30	0.15-0.25		
Super Rapid Extra	0.65-0.75		3.80-4.50	17-18		1.30-1.50		
M Y	0.38-0.48	0.20-0.40	1.25-1.55		1.30-1.70	0.20-0.30		
White Label	0.70-0.80		3.50-4.00	16		0.60-0.75		
H&R #1 High Speed	0.55-0.75	0.15-0.30	3.80-4.25	17.75-18.50	0.20-0.35	0.90-1.25		
H&R Cobalt High Speed	0.75-0.80		4.00	18		1.00		Co 5
H&R K	2.40-2.50	0.25-0.40	12.75-13.25		0.15-0.30	0.15-0.25		

*Also same trade names as Halcomb Steel, Div.

(Continued)

	C	Mn	Cr	W	Si	V	
33. Houghton & Richards,^b Inc., Boston—Continued							
H&R #2 High Speed.....	0.80-0.85		4.00-4.50	18-19	0.20-0.50	2.00-2.25	Mo 0.60 -0.80
H&R Hot Work.....	0.30-0.35		3.00-3.50	10-11.50	0.20-0.35	0.30-3.50	
H&R K-2	1.50	0.25	11.50		0.30	0.25	Mo 0.75
H&R Oil Hardening.....	0.90-1.00	0.90-1.00	0.50-0.60		0.20		
H&R Vanadium	1.05-1.15	0.25			0.20	0.18	
H&R M Y-A	0.40-0.45	0.30	1.40-1.50		1.40-1.50	0.20-0.30	
H&R Grey Label.....	0.90-1.05	0.20-0.30			0.15-0.25		

	C	Mn	Cr	W	V	Ni	Mo
34. Jessop Steel Co.,^a Washington, Pa.							
E. 25	0.75-1.00						
Washington	0.85-1.05				0.15-0.25		
Lion	0.60-1.40						
Chippaway	0.60-1.40						
Dacar	0.95-1.10						
Centaur	0.90-1.05						
Miner's Drill	0.75-0.85						
Extra Tough No. 4.....	0.65-0.75		0.50			1.30	0.25
96 KC	0.60-0.80		0.30			1.50	
139 B	0.70-0.85		0.30			2.50	
Top Notch	0.50		1.25	2.50	0.25		
Magic T. R.	0.50						Si 2
89 MC	0.50-0.60		0.80-1.10		0.15-0.25		
Ball Bearing Steel, 136 ..	1.00-1.10		1.25-1.50				
Special Alloy, 51V.....	1.10-1.20			1.30			
Special Oil Hardening.....	0.90	1.70			0.20		
Truform	0.90	1.20	0.50	0.50			
3 C	2.00-2.20		11.50-12.50				
C.N.S.	1.50		11.00-12.00		0.20		0.80
J Hot Working Die.....	0.60		3.75				
JJ Hot Working Die.....	0.90		3.75				
2 B (HC), Hot Working Die...	0.40-0.50		2.50-3.00	11.50	0.50		
2 B (MC), Hot Working Die...	0.30-0.40		2.75-3.25	13-14	0.50		
2 B (LC), Hot Working Die...	0.28-0.30		2.75-3.25	9.50-10.50	0.50		
Fast Finishing Steel.....	1.25-1.35		0.40-0.50	3.25-3.75			
King Cobalt	0.70-0.80		3.80-4.20	18.00-18.50	0.75-2.10		0.90-1.10
Purple Label Extra.....	0.70-0.80		3.80-4.20	18.00-18.50	1.75-1.90		Co 11.50-12.00 0.70-0.90 Co 8.50-9.00
Purple Label	0.70-0.80		4.30	18.5	1.5		Co 5
Supremus Extra	0.75-0.82		4.00	18.5	2.0		1.0
Supremus	0.70-0.75		4.00	18.00	1.5		
Mogul	0.72-0.82		4.00	15.00	1.00		8.0

	C	Mn	Cr	W	V	
35. William Jessop & Sons, Inc.,^c New York						
Yellow Label	1.00-1.10		0.30-0.40			
Green Label	1.00-1.10		0.30-0.40			
Black Label	1.00-1.10		0.30-0.40			
W. J. & S. Extra.....	1.00-1.10		0.30-0.40			
Composite Die	1.00-1.10		0.30-0.40			
Alloy B (Fin.)	1.40-1.50		0.30-0.40	0.75-0.85	4.0-4.5	
B. B. Hot Die.....	0.40		0.25-0.35	3.5	8-9	0.20-0.40
Alloy C	2.00		0.30-0.40	13.5		
J-4 Chisel	0.45-0.55		0.25-0.30	1.5	2	0.4
Albor	0.85		0.25-0.30	0.65-0.75	2-2.5	
Hack Saw	1.20		0.25-0.30		1.25	
Ark Superior	0.70-0.75		0.30-0.40	4	18	1.4
Ark Superlative	0.70-0.75		0.30-0.40	4	18	1.5 Co 5
Ark Supreme	0.70-0.75		0.30-0.40	5	20	1.75 Co 15
Superior Oil Hardening.....	0.85		1.20-1.40		0.3-0.5	
Circular Plates	1.00		0.30-0.40			

	C	Mn	Cr	W	V	Ni	Mo	Si
36. Kloster Steel Corp.,^{b, c} Chicago								
"Swed Oil" Oil Hard.....	0.95	1.10	0.45	0.40				0.38
"Chiz-Alloy"	0.40	0.40	1.00	1.00			0.25	0.23
Kloster "Rolmo"	1.03	0.46	1.29				0.31	0.36
Kloster Z-457	0.49	0.35	3.00		0.24			0.23
Kloster-B-N-97	0.58	0.40	0.80			3.20	0.41	0.28

(Continued)

	C	Mn	Cr	W	V	Ni	Mo	Si
36. Kloster Steel Corp.,^b • Chicago								
—Continued								
Kloster Hollow Drill	Straight Carbon							
Kloster Solid Drill	Straight Carbon							
Kloster Standard	Straight Carbon							
Kloster Ex-Mejzel	0.50	0.50		1.00			1.00	0.90
"K-L-S-44" Hot Work	0.47		0.90-1.00	1.00			0.25-0.35	
Pure-Ore "Super Alloy"	0.50	0.30	0.95	1.10			0.20	0.20
Pure-Ore "D-C-33" Hot Work	0.30		4.80	1.00-1.25			1.50-1.60	0.90
Pure-Ore "D-C-66"	0.26		3.50	8.50-9.00	0.30			
Pure-Ore "Kapo"	2.00	0.77	12.50	2.00				0.44
Pure-Ore "Hi-Run"	1.50	0.35	12.50		0.23		0.80	0.35
Pure-Ore Double Special	1.15	0.42	0.40	1.29				0.27
Pure-Ore "A-D-70"	0.71	0.36	0.31	0.98	0.12			0.20
Pure-Ore "A-D-95"	1.10	0.36	0.25	0.50	0.12			0.21
Pure-Ore No. 14	1.00	0.35	0.45					0.23
Pure-Ore No. 10	0.64	0.76	0.80		0.20			0.35
Pure-Ore "V-995"	1.00	0.21	1.15	0.10				0.15
Pure-Ore Cold Heading								
Pure-Ore Clipper	0.55-0.75	0.15-0.35	3.80-4.25	18.50	0.90-1.24			0.20
Pure-Ore "Prior"	0.78-0.84	0.25-0.35	4.00-4.50	18.50	2.00-2.25		0.50-0.80	0.25
Pure-Ore Cobalt Hi-Speed ..	0.72-0.80	0.25-0.30	4.00-4.50	14.50	2.00-2.50		0.40-0.60	0.25
						Co 4.75-5.00		
Prior Extra Hi-Speed	0.69	0.35	4.81	19.00	0.93	Co 1.05		0.30
Pure-Ore No. 25	1.10		0.40	1.50				
Pure-Ore Special								
Pure-Ore Extra	Straight Carbon Steels							
Pure-Ore Standard								
Pure-Ore Flapper Valve Spring Steel								

	C	Cr	W	Mo	V	Ni
37. Latrobe Electric Steel Co.,^a Latrobe, Pa.						
Electrite No. 1	0.72	4.00	18		1.00	
Electrite Uranium	0.70	4.00	14		1.50	
Electrite Cobalt	0.70	4.00	17.50		1.00	Co 4
Electrite Super Cobalt	0.75	4.00	18.00		2.00	Co 8
Electrite Ultra Cobalt	0.75	4.00	18		1.75	Co 12
Electrite No. 19	0.80	4.00	18.50	0.60	2.10	
Electrite Vanadium	1.00	4.00	18.00	0.80	3.25	
Tatmo	0.80	3.75	1.50	8.50	1.00	
E.H.W. No. 1	0.25	4.00	15		0.50	
E.H.W. No. 2	0.50	3.00	15		0.50	
E.H.W. No. 3	0.30	3.00	9.50		0.50	
Special Carbon	0.70-1.40					
Extra Carbon	0.70-1.40					
Standard Carbon	0.70-1.40					
G.S.N.	2.20	13				Ni 0.50
G.S.N. Special	1.50	11.50		0.75	0.25	
X.L. Chisel	0.50	1.40	2.00		0.25	
Renown (Die Steel) ..	0.75-1.20				0.20	
Select (Hot Work)	1.00	4.00				
C.F.S. (Die Steel)	0.70-1.40	0.50				
Arrow	0.25	1.00			0.20	
Crown	0.50	1.00			0.20	
Aldivan (Die Steel) ..	0.45	2.50			0.25	
Supreme	0.60	1.00			0.20	
Superb	0.75	1.00			0.20	
Mangano Special	0.95	0.50	Mn 1.15	0.50		
Lumdie	0.40	5.00	4.50			Co 0.50 Si 0.90

	C	Mn	Cr	W	Mo	V	Ni
38. Lehigh Steel Co.,^b New York							
"Leco" Non-Tempering	0.33	0.60	0.75		0.75	Cu 0.70 Si 0.65	Ti 0.05
"Leco" X	0.45	0.60	0.75		0.75	Cu 0.70 Si 0.65	Ti 0.05
Lehigh XXX	0.70		4.00	18		V 1.00	
Lehigh S.S.	0.75		4.00	20	0.75	V 2.00	Co 12
"Hycro"	2.00	0.30	12.50		0.75	V 0.90	Si 0.30
"Ferno"	0.70		3.75		0.70	V 0.55	
"Torpedo"	0.90	1.20	0.50	0.50			Si 0.30
"Conqueror"	0.70-1.10	0.40			0.25		Si 0.30
"Croma"	0.33	0.80	1.00				Si 0.30
N.C. Alloy	0.60	0.40	1.00				Ni 1.50

(Continued)

TOOL STEEL TRADE NAMES

29

	C	Mn	Cr	W	Mo	V	Si	Co
39. Ludlum Steel* Co.,* Water-vliet, N. Y.								
Super Panther	0.80		4.00	19.00	1.00	2.00		7
Panther Special	0.70		4.00	19.00		1.00		5
ML	0.80		4.00	18.00	0.75	2.00		
LXX	0.70		4.00	18.00		1.00		
LMW	0.75		4.00	1.50	8.00	1.00		
Mohawk	0.50		3.50	14.00		0.70		
Atlas B	0.40		3.50	11.00		0.45		
Atlas A	0.30		3.50	9.00		0.45		
EB Alloy	0.65		3.75		0.70	0.55		
Seminole Medium	0.43		1.30	2.00		0.25		
Seminole Hard	0.48		1.30	2.00		0.25		
Ludlum 802	0.48	0.70			0.40		1 70	
Python	0.90					0.25		
Atlas 93	0.55	0.55	0.65		0.35			
Ontario	1.50		12.00		0.80	0.25		
Huron	2.00		12.00			1.00		
Deward	0.90	1.50			0.30			
Saratoga	0.90	1.20	0.50	0.50				
Utica	1.25		0.40	1.40		0.20		
Pompton Special	0.70-1.40							
Pompton Extra	0.70-1.40							
Pompton	0.70-1.40							
Corinth	0.70-1.10							
Crow	1.20		0.50					
Albany	0.75	0.60	1.00			0.20		
Caroga	0.50	0.65	1.00			0.20		
Teton	1.00		1.50					
Special M	1.20		0.20			0.15		
XCM	1.20	0.65	1.40		0.45			
LSD	1.00		1.25		0.30			

	C	Mn	Cr	W	V	Si	Co
40. McInnes Steel Co.,* Corry, Pa.							
Misco "A" (Reg. C)	0.70-0.80						
Superior (Ex. C)	0.90-1.10						
Vanadium Crucible (V)	0.75-1.00	0 25-0.35			0.15-0.50		
McInnes Special (Sp.C)	0.95-1.10						
Special Chrome Nickel (Die Steel)	0.50-0.90			0.60-0.90			Ni 1.25-1.50
Record "A" (WO)				1.50-8.00	7-9	0.20-0.80	
"V" High Speed (V, W)				4.00	18	1.25	
Cello Vanadium (V)		1.00-1.75					
Misco "B" (Reg. C)	0.80-0.90						
McInnes "Cobalt" (V.W.Cob)			4.00	18			Co 3-6
Folder Die (Reg. C)	(Not available)						

	C	Mn	Cr	W	Mo	V	Ni	Co
41. The Midvale Co.,* Philadelphia								
Carbon Tool (Reg., Spec., Extra)								
Die Block B—(C)	0.80	0.25						
Alloy No. 6—(Cr)	1.05		1.00					
Smoothhole (Hollow Drill) (C)	0.85							
Bit Steel (C, Mn)	0.70	0.75						
Jar Steel (C, Mn)	0.60	0.78						
Bolt Die Regular (Cr)	1.00		4.00					
Bolt Die Special (Cr, W)	0.35		1.75	11		0.25		
Die Block C—(Cr, Ni)	0.45		0 75			1.50		
Duredge Chisel—(Si, Mo)	0.55				0.50			Si 1.60
Finishing (Cr, W)	1.45		0.75	4.25				
Multole Punch—(Mn, Si)	0.57	0.70						Si 2.00
Nut Piercer—(Cr, W)	0.40		3 25	9.50				
Salvo Rivet Set—(Ni, V)	0.60		1.00			0.20	2.20	
No. 77 Tool Steel (Cr, Mo)	1.00		1.30		0.30			
One Star High Speed—(Cr, W, V)	0.70		3.50	14		2.00		
Two Star High Speed—(Cr-W-V)	0.70		3.50	18		1.00		
Three Star High Speed—(Cr, W, V, Mo, Co)	0.70		3.75	18	0 55	1.25		5.5
Five Star High Speed—(Cr, V, W, Mo, Co)	0.85		4.25	18.50	0.55	2.50		10.5
Constant—(Mn, Cr, W)	0.90	1.00	0.50	0.50				
Diamond Brand—(Cr)	1.70		18.00					
Double Extra Carbon (Cr)			0.50					
Tool Holder—(Cr, W, Mo)	1.25		3.00	13	1.25			
Chrome Roll (Cr)	1.00		2.00					
Caroph (Open Hearth Carbon Tool Steel)								

*Name changed to: Allegheny Ludlum Steel Corp.

(Continued)

	C	Mn	Cr	W	Mo	V	Co
42. A. Milne & Co.,^b New York							
Imperial Major			4-5	21-22	0.50	0.50-1.00	13
Hyco			4-4.25	18-18.50		1.30	3-5.50
Hyvan			4-4.25	19		2.25	
AMC			4	18		1.30	
Max Tack	2.25		12	11.25		0.10	
Tungsten Hot Work	0.40-0.45		2.50	8-10		0.10-0.15	
Fast Finishing	1.25-1.35			3.50-5.00			
Double Seven	1.30-1.35		13.30				3.45
Double Six	2.25		14				
High Production	1.55		11.50		0.75		
K9	0.90	1.00	0.70	0.50			
Amcoh	0.85-0.90	1.00-1.25	0.40-0.60	0.70			
Special Chrome Vanadium	0.65		0.90			0.20-0.25	
Chrome Hot Work	0.90		3.75				
Tube Mandrel	1.15-1.35		0.35				
Minerva Chisel	0.50-0.55	0.42	1.75	1.90-2.00		0.20	
A020	0.45-0.50		1.25-1.75	2.00-2.50		0.20-0.30	
F.P.C. Chisel Steel	0.30-0.40	0.60-0.80	0.70-0.90		0.30-0.60		
Sp. Vanadium	0.80-1.10	Under .30				0.10-0.20	
Orange Label	1.05-1.10						
Red Label	0.95-1.00						
White Label	0.90-1.00						
Green Label	0.70-0.80						
	C	Mn					
43. Patriarche & Bell,^b New York							
Bell Special	0.90-1.05						
Bell Brand	0.70-0.80						
P. B.	0.60-0.70						
	C	Mn					
44. Horace T. Potts Co.,^b Philadelphia							
Trojan No. 8	0.75-0.85	0.30-0.50					
Trojan No. 9½	0.90-1.00	0.30-0.50					
Solid Drill	0.80-0.90						
Hollow Drill	0.80-0.90						
Potts Special Drill Rod	0.95-1.05	0.30-0.50					
Elastuf Type A (Cr, V)	0.45-0.55						
	C	Mn					
45. Pratt & Inman,^b Worcester, Mass.*							
46. A. E. Purdy Co., Inc.,^b New York							
Planet Drill Rod	1.05-1.15						
Planet Choice	0.95-1.35						
Planet Extra	0.90-1.05						
Planet Special	0.90-1.05						
Planet Regular	0.90-1.05						
	C	Mn	Cr	W	V	Mo	Si
47. Joseph T. Ryerson^b & Son, Inc., Chicago							
Ryerson VD	0.95-1.05	0.27			0.15-0.18		0.19-0.21
Ryerson BFD	1.15-1.25		0.60-0.70	1.50-1.75	0.20-0.25		
Ryerson Shock Steel	0.45-0.55		1.20-1.50	1.50-2.00	0.20-0.30	0.20-0.30	
Ryerson High Speed			4.00	18.00	1.00		
Ryerson L.L.D.	2.00		12.00		0.25		
	C	Mn	Cr	W	V	Mo	Si
48. S K F Steels, Inc.,^c New York							
S K F #1	1.00	1.05	1.05				0.80
S K F #2	0.95	1.60	1.55				0.80
S K F #3	1.00		1.50				
S K F #7	1.10		0.65				
S K F #9	1.10		0.50				

*Pratt & Inman have the same trade names as Columbia Tool Steel Co.

(Continued)

	C	Mn	Cr	W	V	Mo	
48. S K F Steels, Inc.,^c New York—							
Continued							
S K F #13.....	1.05		1.00				
S K F #22.....	1.00		1.15			0.35	
S K F #36.....	2.15	1.20	12.00		0.15		
S K F #46.....	0.90	1.15	0.50	0.50	0.15		
S K F #48.....	1.50		12.00		0.30	0.80	
S K F #55.....	0.85				0.10		
S K F #100.....	1.05						
S K F #300.....	0.30		3.50	9.50	0.40		Ni 1.00
S K F #711.....	0.50		1.15	2.50	0.15		Si 0.75

	C	Mn	Cr	W	V	Mo	
49. Simonds Saw & Steel Co.,^a Lockport, N. Y.							
Diamond "S"	0.80-1.25						
Blue Label	0.80-1.25						
Red Label	0.80-1.25						
Die Steel No. 13200.....	1.80		12.50		0.10		
Red Streak	0.70		4	18	1		
Super Cobalt	0.80		4	18.25	1.85	0.50	Co 8
Teenax	0.95	1.50					
O.H.D.	1.20		0.60	1.65	0.25		

	C	Mn	Cr	W	V	Mo	
50. Swedish Steel Mills' A. A. Inc.,^c New York							
Fagersta Special	1.00	0.35					Si 0.15
Fagersta Extra	1.00	0.35					Si 0.15
Fagersta Regular	1.00	0.35					Si 0.15
Fagersta Cold Heading.....	1.05	0.35			0.50		Si 0.20
Fagersta Non Deforming.....	0.85	1.05	0.45	0.45			
Fagersta High Production.....	1.60	0.30	12.00		0.20	0.80	Si 0.30
Fagersta Broach	1.15	0.40	0.40	1.25			Si 0.25
Fagersta Fast Finishing.....	1.35	0.35	0.60	3.25			Si 0.35
Fagersta Alloy Chisel.....	0.45	0.25	0.90	1.00		0.20	Si 0.20
Fagersta Hot Die.....	0.30	0.30	3.50	9.00	0.40		Si 0.45
Fagersta Die Casting.....	0.50	0.35	3.00		0.25		Si 0.20
Fagersta A D 95 Coining Die.....	0.70		0.25	1.00	0.15		
Fagersta Polhem Wire Drawing.....	1.80	2.00	2.00	13.00			
Fagersta Brilliant H.H.....	0.70		3.50	14.00			
Fagersta Brilliant A.X.....	0.70		4.00	18.00	0.75		
Fagersta Brilliant W W.....	0.70		4.50	18.00	1.50		
Fagersta Brilliant W K E.....	0.70		4.50	18.00	1.50	1.00	Co 5
Fagersta Brilliant W K E Extra.....	0.70		4.50	19.00	1.50	1.00	Co 9
Fagersta Cutlery	1.10	0.20					Si 0.25
Fagersta Overcoat Axe.....	1.00	0.25					Si 0.15
Fagersta Engraver Plates.....	0.35	0.30					Si 0.10
Fagersta Shoe Die	0.90	0.35					Si 0.15
Fagersta Envelope Die.....	0.90	0.35					Si 0.15
Fagersta Alloy Shoe Die.....	0.50	0.60	0.60		0.40		
Fagersta Pavement Breaker.....	0.65	0.30					Si 0.10
Fagersta Solid Drill Steel.....	0.85	0.30					Si 0.10
Fagersta Hollow Drill Steel.....	0.80	0.30					Si 0.10
Fagersta Relled Auger.....	0.85	0.30					Si 0.10
Fagersta Alloy "30" Drill.....	1.00	0.30	1.10		0.35		Si 0.30

	C	Mn	Cr	W	Mo
51. Tennessee Coal, Iron & Railroad Co.,^a Birmingham, Ala.					
Tennessee Special	0.90-1.01	0.50 max.			

	C	Mn	Cr	W	Mo
52. Timken Steel & Tube Div., Timken Roller Bearing Co.,^a Canton, Ohio					
Graph-sil	1.50	0.40 max.			Si 0.85-0.95
Graph-Mo	1.50	0.40 max.		0.20-0.30	Si 0.75-0.85

	C	Mn	Cr	W	V	Mo
53. Uddeholm Co. of America, Inc.,^c New York						
UHB Standard	1.05					
Triangle X Extra.....	1.05					
Triangle X Special.....	1.05					

(Continued)

	C	Mn	Cr	W					
53. Uddeholm Co. of America, Inc.,^c New York—Continued									
UHB Cold Heading.....	0.95								
UHB-46 (Mn, Cr, W) Oil Hardening	0.90	1.10	0.50	9.50		V 0.10			
TRI-MO (C, Cr, Mo) Air Hardening	1.50		12.00		0.80	V 0.20			
UHB Fingal (Cr, W, Mo) Impact Steel	0.50		1.00	1.00	0.25				
UHB Regin (Cr, W) Hot Work.....	0.45		1.00	2.50					
UHB Valand (Cr, Ni, W) Hot Work	0.30		2.50	9.50		V 0.20		Ni 1.75	
UB Double Bolt Hollow Drill Steel..	0.75								
UB Double Bolt Alloy Hollow Drill Steel	0.95		1.10	0.20					
	C	Mn	Si	Cr	V	W	Mo	Co	Ni

54. Universal-Cyclops Steel Corp.,^a Bridgeville, Pa.									
Cyclops Special	0.65-1.35								
Cyclops Extra	0.65-1.35								
Cyclops Standard	0.65-1.35								
Draco V.....	0.65-1.15				0.25				
Ajax	0.95			3.75	0.25				
Titus	0.75			0.75	0.25				
Orion	0.50			1.00	0.25				
Apollo	0.50	0.75		2.25	0.25				
Saturn	1.25					3.50			
Alco	0.45			1.50	0.25	2.25			
Para	0.65-1.35			0.40	0.25	1.60			
Venango	0.50		1.10		0.20		0.50		
Wando	0.95	1.05		0.50	0.25	0.50			
Ultradie #1	2.25			13.00	0.25				
Ultradie #2	1.50			11.50	0.20		0.80		
Alloy B	1.05			1.35					
67	0.55	0.80	2.00				0.20		
N-9	0.60			1.00					1.50
B-4	0.45			3.50		13.25			
B-6	0.55-0.75			4.00	1.00	18.00			
B-7	0.70			4.25	1.10	18.00	0.50	5.00	
B-8	0.75			4.25	2.25	14.00	0.50	5.00	
B-9	0.80			4.25	2.25	18.50	0.70		
MoTung	0.65-0.82			4.00	1.10	1.50	8.25		
Super MoTung	0.78			4.00	1.25	1.50	8.50	5.00	
	C	Mn	Cr	W	V	Mo	Co	Si	
K-L	0.35	0.60	7.50	7.50					1.50
K-M	0.45	0.60	7.50	7.50					1.50
K-R	0.55	0.60	7.50	7.50					1.50
K-S	0.35	0.65	5.25	5.25	0.25	0.25	0.50	0.90	
Thermold ..	0.35	0.50	5.25		0.30	0.90		0.90	
	C	Mn	Cr	W	V	Co			

55. Vanadium-Alloys Steel Co.,^a Latrobe, Pa.									
Latrobe	0.60-1.30								
Special	0.60-1.30				0.20				
Colhed	0.95				0.50				
Crocar	2.15		12.00		0.75	0.75			Si 0.30
Marvel (Hot Work).....	0.33		3.50	9.50	0.45				
Extrude Die (Hot Work).....	0.38		3.00	15.50					Mo 3, Ni 2
Hotform (Hot Work).....	0.32	0.25	4.75	0.90					Mo 1.15, Si 0.90
C.M. Tap	1.25	0.60	0.50						
Croman	1.20	0.85	0.50						Mo 0.60, Si 0.25
Choice	0.90-1.05		3.70-4.10						
Par-Exc (Die Steel).....	0.50		1.65	2.00	0.25				
Vanadium	0.45-1.00		0.80		0.20				
Red Cut Superior.....	0.50-0.75		4.00	18.00	1.05				
E. V. M.....	0.80		4.25	18.50	2.10				Mo 0.65
Red Cut Cobalt.....	0.72		4.00	18.00	1.00	4.50			Mo 0.75
Gray Cut Cobalt.....	0.80		4.25	20.50	1.40				Co 12.25, Mo 0.6
Non-Shrinkable	0.95	1.30	0.50	0.50	0.20				
Vascoloy-Ramet (Made in 15 compositions)									
	C	Mn	Cr	W	Mo	V			

56. Vulcan Crucible Steel Co.,^a Allquippa, Pa.									
Special			Not available						
Extra			Not available						
Port Pitt			Not available						
Special Vanadium			As required					0.30-0.35	
Hecla			Not available						

(Continued)

	C	Mn	Cr	W	Mo	V
56. Vulcan Crucible Steel Co.,^a Alliquippa, Pa.—Continued						
Auto		Not available				
Heavy Duty		Not available				
4870		Not available				
Hardrite	1 10		0 60	1.75		0.25
Non-Shrinkable	0.90	1.50-1.60	0.20-0.25			
K. R.		Not available				
Extra Chrome	0.90		3.75			0.20
Alldie	1.55		12.00		0.75	0.25
Hi-Pro	2.20		12.00			
4-H-W		Not available				
6-H-W		Not available				
A-41		Not available				
Regal	1.35		0.40-0.50	5.50		
Calo Ferro	(0.30)		3.50	9.00		0.25
	(0.45)		3.00	13.00		0.25
Wolfram			4.00	18		1.00
Super Steel			4.00	19	0.75	2.00
Wolfram Cobalt		Not available				
A-42		Not available				
Q. A.		Not available				
Blue Edge		Not available				
Vulmo		Not available				

	C	Mn	Cr	W	V
57. Edgar T. Ward's Sons Co.,^b Pittsburgh					
Washington	0.60-1.40				
Lion	0.60-1.40				
Chippaway	0.60-1.40				
Domestic	0.60-1.40				
Centaur	0.90-1.05				
High Carbon Alloy	1.10-1.30			1.00-1.50	
2 B Hot Die	0.40-0.50		2.50-3.00	11.50	0.50
JJ Hot Work	0.90		3.75		
Hot Stamping Alloy Die	0.60		3.75		
Shock Resisting	0.75-1.05				0.15-0.25
Special Oil Hardening	0.90	1.70			0.20
Top Notch	0.50		1.25	2.50	0.25
Supremus Extra	0.75-0.82		4.00	18.50	2.00
Supremus	0.70-0.75		4.00	18.00	1.50
Purple Label	0.70-0.80		4.30	18.50	1.50 Co 5
Truform	0.90	1.20	0.50	0.50	
3-C Die	2.00-2.20		11.50-12.50		

	C	Mn	Cr	W	V
58. Wheelock, Lovejoy & Co., Inc.,^b Cambridge, Mass.					
Wheelco Superior (C)		As specified			
Wheelco Standard (C)		As specified			
Wheelco Alloy Tap (Cr, V, W) ..	1.20		0.75	1.50	0.20
Wheelco Finishing (Mo, W)	1.30			4.00	
Wheelco Hot Die (Cr)	0.85		3.75		
Wheelco High Speed (W)	0.70		4.00	18.00	1.0
Wheelco Oil Hardening (Mn)	0.90	1.20	0.50	0.50	0.20

	C	Mn	Cr		
59. Ziv Steel & Wire Co.,^b Chicago					
Zivco		Not available			
Hollow Drill		Not available			
Rolled Auger		Not available			
Solid Drill		Not available			
Ziv's Reg., Ex., Sp. C.		Not available			
Normar		Not available			
VanDieCar	1.10-1.15		0.20-0.40		V 0.25-0.35
Hargus	0.90-0.95	0.90-1.00	0.30-0.40		
Lophos		Not available			
Wizard		Not available			
Cobalt		Not available			
Red Shadow		Not available			
Super		Not available			
Neor	2.3	0.40	13		Ni 0.60, Si 0.60
PRK 33		Not available			
Zip		Not available			
Straus Metal (Tantalum Carbide) ..					
Plancher	0.60-0.70	0.70-0.90			Si 1.90-2.10
Hobalite		Not available			
BRM		Not available			
DO-IT	0.60-0.70	0.70-0.90			Si 1.90-2.10 Mo 0.15-0.25

^aManufacturer; ^bDealer; ^cImporter. (Continued)

TRADE NAMES OF TOOL STEELS

(Alphabetically Arranged)

The number preceding each trade name indicates the firms listed in the first section of this compilation. The approximate composition of the important alloying elements is also given with the trade name and the firms.

A			B			C		
17. A-B-O			6. Best Carbon			13. Columbia Double Special		
4. A-C-T H.S.			41. Bit Steel			45. Columbia Double Special		
42. AMO			15. Black Diamond Tool			13. Columbia Electrex		
42. AO20			35. Black Label			45. Columbia Electrex		
56. A-41			3. Blue Anchor Drill Rod			13. Columbia Extra		
56. A-42			26. Blue Chip			45. Columbia Extra		
1. Achorn Fagersta Brands			56. Blue Edge			13. Columbia Double Special		
1. Achorn Kloster Brands			32. Blue Label			45. Columbia Double Special		
29. Air Hardening			33. Blue Label			13. Columbia Electrex		
15. Airdi			49. Blue Label			45. Columbia Electrex		
13. Airex			41. Bolt Die Regular			13. Columbia Extra		
45. Airex			41. Bolt Die Special			45. Columbia Extra		
16. Ajax			7. Bonded Carbide			13. Columbia Extra Vanadium		
54. Ajax			6. Bowco Oil Hardening Tubing			45. Columbia Extra Vanadium		
21. Albany			6. Bowco Water Hardening Tubing			13. Columbia Special		
39. Albany			5. Broaching			45. Columbia Special		
35. Albor			32. Brown Label			13. Columbia Standard		
16. Alco			33. Brown Label			45. Columbia Standard		
54. Alco			13. Buster (Shock Resisting)			13. Columbia Standard Vanadium		
37. Aldivan			45. Buster (Shock Resisting)			45. Columbia Standard Vanadium		
56. Alldie						11. Comet		
16. Alloy B						5. Comokut High Speed		
35. Alloy B						5. Composite Die		
54. Alloy B						38. "Conqueror"		
35. Alloy C						41. Constant		
41. Alloy No. 6						21. Corinth		
15. Alva Extra						39. Corinth		
15. Alva Special						14. Crasco Brands		
42. Amcoh						15. Crescent Double Special		
16. Apollo						15. Crescent Extra		
54. Apollo						15. Crescent Hot Work		
35. Ark Superior						15. Crescent Rim Roll		
35. Ark Superlative						15. Crescent Special		
35. Ark Supreme						15. Crescent Special Alloy Chisel		
37. Arrow						15. Crescent Tool		
6. Arrow Oil Hardening						2. Creston		
13. Artidle						24. Crocar		
45. Artidle						55. Crocar		
15. Atha Chrome Roll						20. Oroloy		
15. Atha Pneu						38. "Croma"		
15. Atha Rim Roll						55. Croman		
4. Atlantic Die Steel						26. Cromovan		
4. Atl. H. S. Steel						21. Crow		
4. Atlantic No. 33 and No. 44						39. Crow		
21. Atlas A						37. Crown		
39. Atlas A						6. Crown W Fast Finishing		
21. Atlas B						13. Cutter Alloy		
39. Atlas B						45. Cutter Alloy		
8. Atlas "Q"						16. Cyclops Extra		
21. Atlas 93						54. Cyclops Extra		
39. Atlas 93						16. Cyclops Special		
8. Atlas Double Extra						54. Cyclops Special		
8. Atlas Extra						16. Cyclops Standard		
8. Atlas Refined						54. Cyclops Standard		
8. Atlas Special Alloy								
8. Atlas Triple Extra								
4. Atasco Special								
56. Auto								
B			C			D		
35. B. B. Hot Die			15. C.C.A.			59. DO-IT		
6. B.M.S. Plate			29. C.O.S. Die Casting			11. D.Y.O.		
59. BRM			37. C.F.S. (Die Steel)			20. D-1		
6. B. W. Point 5			55. C. M. Tap			20. D-6-Co		
16. B-4, 6, 7, 8 and 9			34. C. N. S.			20. D-9-Va		
54. B-4, 6, 7, 8 and 9			26. C.Y.W. Choice			20. D-29		
8. Badger			18. C-4			34. Dacar		
34. Ball Bearing Steel, 136			56. Calo Ferro			28. Dannemora A D 95 Coining Die		
5. Bearing			17. Cannon			17. Darwin #1, #505, #1366		
5. Bearing (Standard)			17. Cannon-Special			18. Delaware Extra		
43. Bell Brand			10. Carbology			18. Delaware Standard		
43. Bell Special			19. Carbmang			18. Delsteel Alloy		
5. Best			41. Carbon Tool			21. Deward		
20. Best			3. Carbon Vanadium Drill Rod			39. Deward		
26. Best			21. Caroga			26. Diamond "M"		
			39. Caroga			49. Diamond "S"		
			41. Caroph					
			11. Carpenter Moly					
			18. Cartun					
			19. Castaloy					
			20. Celero					
			5. Cellini					
			40. Cello Vanadium					
			34. Centaur					
			57. Centaur					
			15. Champion Extra					
			15. Champion Non-Changeable					
			5. Channeller					
			26. Chimo					
			34. Chippaway					
			57. Chippaway					
			36. "Chiz-Alloy"					
			55. Choice					
			42. Chrome Hot Work					
			41. Chrome Roll					
			7. Chrome Vanadium					
			26. Circle C					
			35. Circular Plates					
			13. Clarite High Speed					
			45. Clarite High Speed					
			5. Cobafux "A"					
			5. Cobafux "B"					
			7. Cobalt					
			59. Cobalt					
			17. Cobaltrom PRK-33					
			12. CoCo Turning					
			25. Cold-Hot					
			32. Cold Label Peerless					
			55. Colhed					
			5. Collet					
			12. Colonial No. 3, 4, 6, 7, 14, 38					
			24. Colonial 6, 14					

(Continued)

D			G			K		
41. Diamond Brand			24. Gray Cut Cobalt			34. King Cobalt		
41. Die Block B			55. Gray Cut Cobalt			7. Kisk		
41. Die Block C			32. Gray Label			36. Kloster Brands		
6. Die Cast			32. Green Label			19. Krokology		
7. Die Casting			35. Green Label			2. Kromal		
32. Die L			42. Green Label			29. Krosil Chisel		
49. Die Steel No. 13200			33. Grey Label			29. Krovan		
57. Domestic			3. Gold Anchor Drill Rod			20. Kutkwik		
41. Double Extra Carbon			11. Gold Star					
42. Double Seven								
42. Double Six								
26. Double Special								
29. Double Special								
16. Draco V								
54. Draco V								
29. Dreadnought High Speed								
18. Drillalloy								
41. Duredge Chisel								
25. Durodi								
2. Dymal								
E			H			L		
21. EB Alloy			17. "H"			26. L. C. Blue Chip		
39. EB Alloy			18. HC-HO			29. L.C.T. Alloy		
8. E. B. Alloy			28. H. M. Blue Chip			29. L.C.T. No. 2		
37. E.H.W. No. 1, No. 2, No. 3			5. H. M. High Speed			29. L.L.C.T.		
24. E. V. M.			33. H&R Brands			21. LMW		
55. E. V. M.			20. H.R.W.			39. LMW		
6. E. Z. 9 W Hot Die			28. H. V. Blue Chip			21. LSD		
6. E. Z. 14 W Hot Die			5. H. V. High Speed			39. LSD		
34. E-25			15. H.Y.C.C.			26. L. T. Forging Steel		
44. Elastuf Type A			35. Hack Saw			21. LXX		
22. Elberts Brands			29. Halcomb 999 High Speed			39. LXX		
32. Electric Brand White Label			29. Halcomb Hot Work			15. La Belle Brands		
37. Electrite Brands			29. Halcut			55. Latrobe		
11. Excelo			29. Haldi			38. "Leco" Non-Tempering		
13. Exl-Die			11. Hampden			38. "Leco" X		
45. Exl-Die			58. Hardrite			5. Lehigh Die and Tool, "H"		
7. Extra			59. Hargus			Temper		
11. Extra			30. Hawk Brands			5. Lehigh Die and Tool, "L"		
20. Extra			31. Haynes Stellite J-Metal			Temper		
26. Extra			56. Heavy Duty			38. Lehigh S. S.		
56. Extra			56. Hecia			38. Lehigh XXX		
27. Extra G			56. Hi-Pro			29. Liberty		
33. Extra M G			57. High Carbon Alloy			34. Lion		
37. Extra Carbon			42. High Production			57. Lion		
56. Extra Chrome			59. Hobalite			59. Lophos		
6. Extra Fraz			44. Hollow Drill			21. Ludium 602		
29. Extra Special			59. Hollow Drill			37. Ludium 602		
5. Extra Special High Speed			8. Hot Die					
34. Extra Tough No. 4			7. Hot Die No. 2					
29. Extra Warranted			57. Hot Stamping Alloy Die					
55. Extrude Die			24. Hotform					
F			55. Hotform					
25. FM			21. Huron					
8. F N S			39. Huron					
42. F. P. O. Chisel Steel			6. Hy-Lo Oil Hardening					
25. FS			38. "Hyco"					
25. FX			42. Hyco					
28. Fagersta Brands			6. Hypro No. 62					
50. Fagersta Brands			42. Hyvan					
8. Falcon								
42. Fast Finishing								
34. Fast Finishing Steel								
38. "Ferno"								
5. Finishing								
41. Finishing								
17. Firex								
17. Firex-Special								
41. Five Star High Speed								
40. Folder Die								
13. Formite								
45. Formite								
56. Fort Pitt								
G			I			M		
37. G.S.N.			24. Ideal			21. ML		
37. G.S.N. Special			17. Ideor			39. ML		
15. Granada Tool			42. Imperial Major			33. M Y		
52. Graph-Mo			6. Impress			34. Magic T. R.		
52. Graph-sil			26. Invaro Oil Hardening			2. Malax		
						2. Malga		
						2. Malgaloy		
						37. Mangano Special		
						20. Mansil Oil Hardening		
						29. Marathon		
						19. Martin Steel		
						55. Marvel		
						42. Max Tack		
						13. Maxite Super High Speed		
						45. Maxite Super High Speed		
						40. McInnes "Cobalt"		
						40. McInnes Special		
						26. Meteor		
						34. Miner's Drill		
						42. Minerva Chisel		
						28. MiRyCal Chisel		
						40. Misco "A"		
						40. Misco "B"		
						7. Mo-Cut		
						34. Mogul		
						21. Mohawk		
						39. Mohawk		
						6. Moldie		
						18. Molel Alloy		
						8. Monark		
						16. MoTung		
						54. MoTung		
						41. Multole Punch		
G			K			N		
37. G.S.N.			16. K-L			16. N-9		
37. G.S.N. Special			54. K-L			54. N-9		
15. Granada Tool			36. "K-L-S-44" Hot Work			17. N-32		
52. Graph-Mo			16. K-M			38. N.C. Alloy		
52. Graph-sil			54. K-M			8. N N		
			16. K-R			5. Nail Die		
			54. K-R			18. National		
			56. K. R.					
			16. K-S					
			54. K-S					
			11. K-W					
			42. K9					
			8. Keewatin					
			29. Ketos					
			20. Keystone Alloy Chisel					

(Continued)

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|---|---|---|
| <p>N</p> <p>17. Neor
49. Neor
30. Nicroman
8. Nipigon
20. Nivan
55. Non-Shrinkable
54. Non-Shrinkable
59. Normar
6. No. 4
6. No. 41
41. No. 77 Tool Steel
29. NuDie Casting
41. Nut Piercer</p> <p>O</p> <p>49. O.H.D.
12. Ohio Die
24. Ohio Die
13. Oldie
45. Oldie
5. Omega
41. One Star High Speed
21. Ontario
39. Ontario
42. Orange Label
32. Orange Label Chisel
16. Orion
54. Orion</p> <p>P</p> <p>43. P. B.
18. P-D Tungsten
59. P R K 33
21. Panther Special
39. Panther Special
24. Par-Exc
55. Par-Exc
16. Para
54. Para
15. Paragon Oil Hardening
15. Peerless A, B, C, and D
29. Peerless Cold Header Die
18. Pennant
5. Permanent Magnet No. 1
5. Permanent Magnet No. 2
13. Phoenix
45. Phoenix
5. Piston
59. Plancher
46. Planet Brands
20. Polaris
28. Polhem Drawing Die
21. Pompton
39. Pompton
21. Pompton Extra
39. Pompton Extra
21. Pompton Special
39. Pompton Special
44. Potts Special Drill Rod
7. Pressurdie No. 1
7. Pressurdie No. 3
36. Prior Extra Hi-Speed
36. Pure-Ore Brands
32. Purple Label
33. Purple Label
34. Purple Label
37. Purple Label
34. Purple Label Extra
29. Pyro
15. Pyro Die
21. Python
39. Python</p> <p>Q</p> <p>56. Q. A.</p> <p>R</p> <p>1. R. B. Special
11. R. D. S.
26. R. T. Steel
40. Record "A"</p> | <p>E</p> <p>3. Red Anchor Drill Rod
24. Red Cut Cobalt
55. Red Cut Cobalt
12. Red Cut Superior
24. Red Cut Superior
55. Red Cut Superior
33. Red Label
42. Red Label
49. Red Label
32. Red Label Peerless
59. Red Shadow
24. Red Star
12. Red Star Tool
12. Red Star Tungsten
24. Red Star Tungsten
49. Red Streak
56. Regal
6. Rekord Eminent
6. Rekord Extra
6. Rekord Select
6. Rekord Superior
37. Renown
15. Rex Brands
9. Rita Brands
59. Rolled Auger
33. Rose Label
47. Ryerson Brands</p> <p>S</p> <p>17. S-I-W
48. S K F Brands
41. Salvo Rivet Set
15. Sanderson Double Special
15. Sanderson Extra
15. Sanderson Special
15. Sanderson Tool
21. Saratoga
39. Saratoga
16. Saturn
34. Saturn
57. Select
13. Self Hardening
45. Self Hardening
20. Semi High Speed
21. Seminole Hard
39. Seminole Hard
21. Seminole Medium
39. Seminole Medium
57. Shock Resisting
12. Silman
13. Silvanite
45. Silvanite
33. Silver Label
26. Silver Star
41. Smoothole
11. Solar
44. Solid Drill
59. Solid Drill
8. Spartan
7. Special
11. Special
26. Special
29. Special
55. Special
56. Special
26. Special A.S.V.
34. Special Alloy, 51V
37. Special Carbon
40. Special Chrome Nickel
42. Special Chrome Vanadium
27. Special G
5. Special High Speed
33. Special K
21. Special M
39. Special M
6. Special No. 18 S
34. Special Oil Hardening
57. Special Oil Hardening
29. Special Vanadium
42. Sp. Vanadium
56. Special Vanadium
13. Special Wire Drawing Alloy</p> | <p>S</p> <p>45. Special Wire Drawing Alloy
6. Standard
7. Standard
20. Standard
29. Standard
37. Standard Carbon
27. Standard G
27. Standard G Chisel
11. Star Zenith
11. Stentor
26. Sterling
26. Sterling Nitrad No. 1
26. Sterling "V"
26. Sterling XX
59. Straus Metal
59. Super
49. Super Cobalt
29. Super Dreadnought High Speed
16. Super MoTung
54. Super MoTung
21. Super Panther
39. Super Panther
33. Super Rapid Extra
56. Super Steel
37. Superb
13. Superdie
45. Superdie
5. Superior
40. Superior
7. Superior No. 1
7. Superior No. 3
35. Superior Oil Hardening
29. Supervan Dreadnought High Speed
37. Supreme
34. Supremus
57. Supremus
34. Supremus Extra
57. Supremus Extra
36. "Swed Oil" Oil Hard</p> <p>T</p> <p>7. T-Alloy
11. T-K
53. TRI-MO
13. Tapdie
45. Tapdie
37. Tatmo
49. Teenax
51. Tennessee Special
21. Teton
39. Teton
2. Thermal
29. Thermo Die
16. Thermold
54. Thermold
41. Three Star High Speed
16. Titus
54. Titus
5. Tong Rein
41. Tool Holder
5. Tool Room Oil Hardening
34. Top Notch
57. Top Notch
38. "Torpedo"
5. Tough, "H" Temper
5. Tough, "M" Temper
5. Tough, "S" Temper
53. Triangle X Extra
53. Triangle X Special
26. Triple Die Steel
8. Trojan
44. Trojan No. 8
44. Trojan No. 9½
34. Truform
57. Truform
42. Tube Mandrel
12. Tungo
42. Tungsten Hot Work
7. Twinvan
41. Two Star High Speed</p> |
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(Continued)

U	W	Numbers
53. UB Double Bolt Alloy Hollow Drill Steel	59. Wizard	5. 6 Nickel
53. UB Double Bolt Hollow Drill Steel	56. Wolfram	23. 7
53. UBH Brands	56. Wolfram Cobalt	5. 7 Nickel
8. Ultimo No. 6	15. Wortle Brands	23. 8
16. Ultradie No. 1 and No. 2	29. Wortle No. 4 Drawing Die	23. 9
54. Ultradie No. 1 and No. 2		23. 9A
21. Utica	X	23. 9B
39. Utica		23. 10
	5. X	23. 11
	5. XCL	23. 12
	21. XOM	23. 13
	39. XCM	23. 14
	26. X.D.H. Steel	23. 16
	26. X.D.L. Steel	23. 17
	26. XDM Steel	23. 18
	37. X. L. Chisel	23. 19
	5. XX	23. 20
	5. XXX	23. 21
		23. 22
	Y	23. 23
	32. Yellow Label	23. 25
	33. Yellow Label	23. 26
	35. Yellow Label	23. 27
		23. 28
	Z	23. 41
	7. Z.N.	23. 42
	59. Zip	23. 43
	59. Ziv's Reg.	5. 57 Hot Work
	59. Zivco	5. 57 Hot Work Special
		23. 61
	Numbers	23. 62
	23. 1	5. 65% Nickel—15% Chromium
	23. 2	16. 67
	57. 2 B Hot Die	54. 67
	34. 2 B (HC) Hot Working Die	5. 67 Chisel
	34. 2 B (LC) Hot Working Die	5. 67 Tap
	34. 2 B (MC) Hot Working Die	32. 70-20M
	23. 3	5. 71 Alloy
	34. 3 C	23. 85
	57. 3-C Die	34. 89 MC
	23. 3½	34. 96 KC
	23. 4	34. 139 B
	56. 4-H-W	5. 445 Hot Work
	23. 5	11. 610 Air Hardening
	23. 6	20. 812 Die Steel
	56. 6-H-W	56. 4870
W		
35. W. J. & S. Extra		
16. Wando		
54. Wando		
54. Washington		
57. Washington		
13. Waterdie		
45. Waterdie		
13. Waterdie B		
45. Waterdie B		
58. Wheelco Brands		
33. White Label		
42. White Label		

Trade Names of Corrosion and Heat Resisting Alloys

(Iron, Chromium, or Nickel Base Alloys)

The manufacturers and the trade names of the corrosion and heat resisting alloys of iron, nickel, or chromium base types are given in this compilation together with the approximate composition of the important alloying elements. The manufacturers are arranged alphabetically and then numbered.

If the trade name is known but not the manufacturer, this can be ascertained by referring to the second section which gives the trade names alphabetically arranged and each name preceded by the manufacturer's number which corresponds with the listing in the first section.

	C	Cr	Ni	
1. Acme Steel Co., Chicago				
Acme Stainless Type 410.....	0.12 max.	10-13.50		
Acme Stainless Type 430.....	0.12 max.	14-18		
Acme Stainless Type 301X.....	0.10-0.20	16-17.50	7-8.50	
Acme Stainless 302.....	0.08-0.20	17.50-19	8-9	
Acme Stainless 304.....	0.08 max.	17.50-19	8-9	
2. Allegheny Steel Co.,* Brackenridge, Pa.				
Allegheny "C" 302.....	0.08-0.20	17.50-19	8-9	
Allegheny "44" 309.....	0.20 max.	22-26	12-14	
Allegheny "33" 410.....	0.12 max.	10-13.50		
Allegheny "66" 430.....	0.12 max.	14-18		
Allegheny "55" 446.....	0.35 max.	23-30		
Allegheny "46" 501.....	Over 0.10	4-6		
3. Alloy Metal Wire Co., Moore, Pa.				
Excelstor			45	Cu 55
Superior		20	80	
Premier		15	62	
Acme		4	30	
Stainless Steels				
Type #302.....	0.08-0.20	17-19	7-9	
#303.....	0.08-0.20	17-19	7-9	
#304.....	0.011 max.	17-19	7-9	
#305.....	0.08-0.20	18-20	8-10	
#306.....	0.11 max.	18-20	8-10	
#307.....	0.08-0.20	19-22	9-12	
#308.....	0.11 max.	19-22	9-12	
Stainless Iron				
Type #410.....	0.12 max.	12-15		
#416.....	0.12 max.	12-15		
#430.....	0.12 max.	15-18		
#442.....	0.35 max.	18-23		
#446.....	0.35 max.	23-30		
4. American Manganese Steel Co., Chicago Heights, Ill.				
Amsco Alloy F-1.....	0.40	16	35	
Amsco Alloy F-3.....	0.35	28	3 max.	
Amsco Alloy F-5.....	0.40	18	65	
Amsco Alloy F-6.....	0.40	12	60	
Amsco Alloy F-8.....	0.30	18	8	
Amsco Alloy F-10.....	0.35	26	12	
5. The American Rolling Mill Co., Middletown, Ohio				
Armco 25-12 309.....	0.20 max.	17.50-19	8-9	
Armco 20-10 307.....	0.08-0.20	20-22	10-12	
Armco 20-10 308.....	0.08 max.	20-22	10-12	
Armco 19-9 305.....	0.08-0.20	18-20	9-10	
Armco 19-9 306.....	0.08 max.	18-20	9-10	
Armco 18-12 SMO 316.....	0.10 max.	16-19	14 max.	
Armco 18-10 Cb 347.....	0.10 max.	17-20	8-12	2-4 Mo Cb 10xC
Armco 18-8 302.....	0.08-0.20	17.50-19	8-9	
Armco 18-8 304.....	0.08 max.	17.50-19	8-9	
Armco 17-7 301X.....	0.10-0.20	16-17 50	7-8.50	
Armco 27 446.....	0.35 max.	23-30		
Armco 17 430.....	0.12 max.	14-18		
Armco RA 434A.....	0.12 max.	14-18		{Si 1.00 {Cu 1.00
Armco 13 410.....	0.12 max.	10-13 50		
6. American Steel & Wire Co., Cleveland (See United States Steel Corp.)				

(Continued)

*These trade names also used by West Leechburg Steel Co., Pittsburgh. See also Ludlum Steel Co.

	C	Cr	Ni	
7. The Babcock & Wilcox Co., New York				
B&W #400.....	0.15 max.	4-6		
B&W #401.....	0.25 max.	4-6		
B&W #402.....	0.10 max.	4-6		
B&W #420.....	0.25 max.	4 5-6.5		W 0.75-1.25
B&W #450.....	0.12 max.	12-14	0.25 max.	
B&W #500.....	0.16 max.	17-19	7.5-10.5	
B&W #502.....	0.07 max.	17-19	7.5-10.5	
B&W #510.....	0.16 max.	17-19	7-10	
B&W #540.....	0.16 max.	16-18.5	8.5-11	Mo 2.5-3.5
B&W #542.....	0.07 max.	16-18.5	8.5-11	Mo 2.5-3.5
B&W #550.....	0.16 max.	22-25	10-13	
B&W #561.....	0.30-0.60	22-25	10-13	
B&W #700.....	0.40-0.60	16-20	62-68	
B&W #701.....	1.0 -1.25	16-20	60-65	
B&W #800.....	1.0 -1.5	24-26	10-12	
B&W #902.....	0.10 max.	17-19		
B&W #910.....	0.25 max.	17-19		
B&W #912.....	0.10 max.	17-19		
B&W #950.....	0.25 max.	26-30		
B&W #1100.....	0.25 max.	24-26	19-21	
B&W #1101.....	0.30-0.50	24-26	19-23	
B&W #1102.....	0.15 max.	24-26	19-21	
B&W #1200.....	0.40 max.	7-9	18-21	
B&W #1300.....	0.50 max.	15-17	35-38	
B&W #1400.....	0.35-0.50	1.25-1.75		W 14-16
B&W #1500.....	0.35 max.	26-28.5	7.5-9.5	
Croloy 12.....	0.12 max.	10-13.50		
Croloy 12-3W.....	0.12 max.	12-14		W 2 50-3.50
Croloy 18.....	0.12 max.	14-18		
Croloy 18-Si.....	0.12 max.	14-18		
Croloy 27.....	0.35 max.	23-30		
Croloy 18-8.....	0.08-0.20	17 50-19	8-9	
Croloy 18-8S.....	0.08 max.	17.50-19	8-9	
Croloy 18-8S Ti.....	0.10 max.	17-20	7-10	Ti Min. 4 x C
Croloy 18-8S Cb.....	0.10 max.	17-20	8-12	Cb 10 x C
Croloy 16-13-3.....	0.10 max.	16-18	14 max.	Mo 2-3
Croloy 25-20.....	0.25 max.	24-26	19-21	
Croloy 27-4-1.....	0.10 max.	25-30	3-5	Mo 1-1.50
8. Bethlehem Foundry & Machine Co., Bethlehem, Pa.				
Bethlehem Tantiron.....	0.08-1.00	0	0	Si 13.50
9. Bethlehem Steel Co., Bethlehem, Pa.				
Bethadur 302.....	Over 0.08-0.20	17.50-19	8-9	
Bethadur 304.....	0.08 max.	17.50-19	8-9	
Bethadur 305.....	Over 0.08-0.20	18-20	9-10	
Bethadur 306.....	0.08	18-20	9-10	
Bethadur 403.....	0.12 max.	11 50-13 50	0.25 max.	
Bethadur 410.....	0.12 max.	10-13.50	0.25 max.	
Bethadur 420.....	0.30-0.40	12-14	0.25 max.	
Bethadur 430.....	0.12 max.	14-18	0.25 max.	
Bethadur 440.....	0.75 mean	14-18	0.25 max.	
Bethadur 440.....	1.15 mean	14-18	0.25 max.	
Bethadur 446.....	0.35 max.	23-30	0.50 max.	
Bethadur 501.....	Over 0.10	4-6	{ With approx. 0.50% Mo or 1.00% W as desired.	
Bethadur 502.....	0.10 max.	4-6		
Bethalon 303.....	0.20 max.	17.50-19	8-9	S 0.25-0.40
Bethalon 303 (alternate).....	0.20 max.	17.50-19	8-9	P 0.20 max.
Bethalon 416.....	0.12 max.	12-14	0.50 max.	Se 0.15 min S 0.30-0.50
10. Braeburn Alloy Steel Corp., Braeburn, Pa.				
Braeburn Stainless.....	0.35	13		
11. Brown, Bayley's Steel Works,¹ Ltd., Sheffield, England				
Brearley-A.....	0.12 max.	12-14		
Brearley-B.....	0.12 max.	14-16		
Brearley-K.....	0.10	16-18		
Lowscore.....	0.10	18-22		
Inventor.....	0.15	12-15		

(Continued)

	C	Cr	Ni	
12. Brown, Bayley's Steel Works,¹ Ltd., Sheffield, England—Continued.				
Engineering	0 20-0.25	13-14		
B. B.	0 25-0.40	12-14		
Twoscore	0 12-0.20	17-20	1.5-2.0	
Anka-O	0.07-0.15	15-17	10-12	
Anka-H	0 07-0.15	17-19	7-10	
Anka-M	0.07-0.15	12-14	12-14	
Arcanka	0 07-0.10	17-20	7-10	
Weldanka	0.05-0.25	18-22	7-12	
BB4K	0.10-0.20	15-19	8-12	Mo 2-4
13. Burgess-Farr Co., Freeport, Ill.				
Illium G.	0 20	20-23	56-58	5-7 Cu 4-6 Mo 1.5-2.5 W
Illium R.	0 10 max.	20-23	56-58	5-7 Cu 4-6 Mo 1.5-2.5 W
14. Canadian Atlas Steels, Ltd., Welland, Ont., Canada				
No-Kor-O 18-8-M	0 10	18	12	Mo 2
No-Kor-O 18-8-S	0.07 max	18	8	
No-Kor-O 18-8	0 10	18	8	
No-Kor-O 25-20	0 20	25	20	
No-Kor-O 18	0.10	18		
No-Kor-O 18-2	0 20	18	2	
No-Kor-O 14	0.35	14		
No-Kor-O 12	0 10	12		
No-Kor-O 12-F	0.10	12		
No-Kor-O 18-F	0 10	18	8	Se 0 25
15. Calorizing Co., Wilksburg, Pa.				
Calite B-28	0.45 max.	25-28	10-12	
Calite B	0.45 max.	21-23	9-10	
Calite A	0.55 max.	15-17	35-37	
Calite N	0 55 max.	17-20	65-68	
Calite N2	0 55 max.	12-14	60-62	
Calite NOT3	0 45 max.	25-27	18-20	
Calite S-28	0.35 max.	25-28	2-3	
Calorized Calite A	0 55 max.	15-17	35-37	35% Al surface
16. Carnegie-Illinois Steel Corp., Pittsburgh. (See United States Steel Corp.)				
17. Carpenter Steel Co., Reading, Pa.				
Stainless Steel-1	0 10	13		
Stainless Steel-N1	0.10	13	2	
Stainless Steel-2	0 30	13		
Stainless Steel-2B	1 00	17		
Stainless Steel-3	0.30	20		Cu 1
Stainless Steel-4	0.10	18	9	
Stainless Steel-5	0.10	13.5		S 0.30
Stainless Steel-6	0.10	17		
Stainless Steel-7	0.15	27		
Stainless Steel-8	0 10	18	9	Se 0 25
18. Chicago Steel Foundry Co., Chicago				
Pyrasteel 2000		26-28	14	
Pyrasteel 20		18	35	
Pyrasteel 18		16	25	
Pyrasteel 14		6		Mo 0 40-0 80
19. Colonial Steel Division, Pittsburgh. (See Vanadium-Alloys Steel Co.)				
20. Columbia Tool Steel Co., Chicago Heights, Ill.				
Stainex #1	0.35	13.5		
Stainex #2	0 65	17		
Stainex #3	0.10	13		

(Continued)

¹Distributed by Joseph Robb & Co., Ltd., Montreal, Que., and Toronto, Ont., and Gordon & Belyea, Ltd., Vancouver, B. C.

	C	Cr	Ni	
21. Cooper Alloy Foundry Co., Elizabeth, N. J.				
Cooper-16	0.12-0.35	14-20		
Cooper-17	0.20 max.	18	8	
Cooper-17Mo	0.20 max.			Mo 3
Cooper-17S	0.10 max.			
Cooper-17SMo	0.10 max.			Mo 3
Cooper-18	0.20 max.	10	22	
Cooper-19	0.50 max.	28		.50-3 max
Cooper-20	0.40 max.	18	36	
Cooper-21	0.40 max.	15	65	
Cooper-21A.B.C.	0.07-0.10	15-20	20-25	Mo 3 Si 1.50
Cooper-21W	0.40	15	25	W 3.5
Cooper-22	0.20-0.50	24-28	10-12	
Cooper-22M	0.20-0.50	24-28	10-12	Mo 3
Cooper-23	0.20 max.	2	40	
Cooper CA-5	0.30 max.	4-6		Mo 0.40-0.65 or W 0.80-1.25
Monel			67	Cu 28 Fe 3
22. Crucible Steel Casting Co., Cleveland				
A. R. Stainless	0.20	18	8	
N C. Heat Resisting	0.25	28	8	
23. Crucible Steel Co. of America, New York				
Rezistal KA2 302	0.08-0.20	17.50-19	8-9	
Rezistal 2C 302B	0.08-0.20	17.50-19	8-9	Si 2-3
Rezistal FM188 303	0.20 max.	17.50-19	8-9	S or Se 0.07 min. or Mo 0.60 max.
Rezistal KA2S 304	0.08 max.	17.50-19	8-9	
Rezistal KA2-199 305	0.08-0.20	18-20	9-10	
Rezistal KA2S-199 306	0.08 max.	18-20	9-10	
Rezistal KA2-2010 307	0.08-0.20	20-22	10-12	
Rezistal KA2S-2010 308	0.08 max.	20-22	10-12	
Rezistal 3 309	0.20 max.	22-26	12-14	
Rezistal 4 310	0.25 max.	24-26	19-21	
Rezistal 7 311	0.25 max.	19-21	24-26	
Rezistal KA2SMO 316	0.10 max.	16-19	14 max	Mo 2-4
Rezistal KA2ST 321	0.10 max.	17-20	7-10	Ti Min. 4 x C
Rezistal 2600 325	0.25 max.	7-10	19-23	Cu 1-1.50
Rezistal 329 329	0.10 max.	25-30	3-5	Mo 1-1.50
Rezistal 330 330	0.25 max.	14-16	33-36	
Rezistal KA2SCB 347	0.10 max.	17-20	8-12	Cb 10 x C Turbine Quality
Rezistal Turbine Quality 403	0.12 max.	11.50-13		
Rezistal Stainless Iron 12-410	0.12 max.	10-13.50		
Rezistal Stainless Iron FM2 416	0.12 max.	12-14		S or Se 0.07 min. or Mo 0.60 max.
Rezistal Stainless Iron Grade A 420	Over 0.12	12-14		
Rezistal Stainless Iron 17 430	0.12 max.	14-18		
Rezistal Stainless Iron 162 431	0.15 max.	14-18	2.00 max	
Rezistal Stainless Iron Grade B 440	Over 0.12	14-18		
Rezistal Stainless Iron 20 442	0.35 max.	18-23		
Rezistal Stainless Iron 27 446	0.35 max.	23-30		
LO-CRO 46 501	Over 0.10	4-6		
LO-CRO 46 502	0.10 max.	4-6		
LO-CRO 46 Mo	0.25 max.	4-6		Mo 0.40-0.60
LO-CRO 46 W	0.25 max.	4-6		W 0.75-1.25
Rezistal Grade B100	0.90-1.10	16-18		
Rezistal Grade BM	1.00 max.	16-20		Mo 0.45-0.65
Rezistal 3-C 309B	0.20 max.	22-26	12-14	Si 2-3
24. Darwin & Milner, Inc., Cleveland				
Pireks-Reactal	0.60	20	65	Si 2
Cobaltcrom (Stainless)	1.10	18		Co 1.10, Mo 1.10
25. Henry Disston & Sons, Inc., Philadelphia				
Stainless Iron	0.12 max.	13.50		
Stainless, Type A	0.30	14		
Stainless, Type B	0.60	17		
Chrome-Nickel A	0.08 max.	18	8	
Chrome-Nickel B	0.16	18	8	
26. Driver-Harris Co., Harrison, N. J.				
Nichrome wire		15	60	
Nichrome castings		13	62	
Nichrome "S"		17	25	
Cimet		26-28	10-12	
Chromax		15	35	
Nichrome V		20	80	

(Continued)

	C	Cr	Ni	
27. Wilbur B. Driver Co., Newark, N. J.				
Tophet "C".....		16	62	
Tophet "A".....		20	78	
Tophet "D".....		20	30	
Gromin "D".....		5	30	
Cupron			44.5	Cu 54
28. Duraloy Co., The, Scottsdale, Pa.				
Duraloy-A	Depends on Service	28		
Duraloy-B	"	18		
Duraloy-C	"	14		
Duraloy-N	"	24	12	
Duraloy-18-8	0.15	18	8	
Duraloy-35-15	Depends on Service	35	15	
29. Durlron Co., Inc., Dayton, Ohio				
Durlron	0.80			Mn 0.35, Si 14.5
Durichlor	0.85			Si 14.5, Mo & Mn
Durimet	0.07 max.	19	22	Mo-Cu-Si
Durco KA2	0.16	18	8	
Durco KA2S	0.07 max.	18	8	
Durco KA2Mo	0.16	18	8	Mo 3
Durco D-10	0.20	23	57	Cu 8, Mo 4, W 2, Mn 1
Durco D-12	0.12	12		
Durco D-18	0.20	18		
Durco D-28	0.20	28		
Durco 24-12	As specified	24	12	
Durco 26-10	"	26	10	
Durco 28-10	"	28	10	
Durco KA2SMo	0.07 max.	18	8	Mo 3
Alcumite				Cu 90, Al 9
30. Electric Steel Foundry Co., Portland, Ore.				
Esco Alloy 40.....	Under 0.20	19	9	
Esco Alloy 45.....	"	19	9	Mo 3
Esco Alloy 43.....	"	25	12	
Esco Alloy 36.....	"	27	3	Mo 1.50
31. The Electro-Alloys Co., Elyria, Ohio				
Thermalloy "A"		20	65	
Thermalloy "72"		12-15	60	
Thermalloy "B"		18	40	
Thermalloy "50"		15	35	
Thermalloy "C"		25-30		
Thermalloy "D"		25-30	2-5	
Thermalloy "E"		25-30	12-14	
32. Empire Steel Castings, Inc., Reading, Pa.				
EM 4-6	Depends on Service	4-6		
EM 12-15	"	12-15		
EM 28	"	27-29		
EM 18-8	"	17-19	7-9	
EM 20-10	"	19-21	9-11	
EM 25-12	"	24-26	11-13	
EM 25-20	"	24-26	19-21	
EM 35-15	"	15-17	35-37	
33. The Fahralloy Co., Harvey, Ill.				
F-1	Depends on Service	18-20	35-38	
F-2	"	21-24	3-6	
F-3	"	26-29	0-3	
F-1260	"	12-15	58-62	
F-10	"	27-30	10-13	
F-2817	"	27-30	16-18	
F-2800	"	27-30		
F-2808	"	26-30	7-9	
F-11	"	14-16	49-51	19-21 Mo \pm W
F-35	"	33-36		
F-35N	"	33-36	9-11	
F-1400	"	12-16		
F-1800	"	16-20		
F-0726	"	6-8	25-27	
F-1824	"	16-19	21-25	
F-1808	"	17-19	7-9	\pm Se \pm Mo
F-0821	"	7-10	21-23	
F-2210	"	20-23	9-11	Plus Al
F-2065	"	18-22	63-66	

(Continued)

	C	Cr	Ni	
34. Firth-Sterling Steel Co., McKeesport, Pa.				
Stainless Type "A".....	0.35	13.5		
Stainless Type "B".....	0.70	17		
Stainless Type "BH".....	0.85	17.50		
Stainless Type "BHH".....	1.05	17.50		
Stainless Type "T".....	0.10	13		
Stainless Type "M".....	0.08	18		
Stainless Type "FC".....	0.10	14		
Nirosta KA2.....	0.16 max.	18	8	S 0.35, Mo 0.40
Nirosta KA2S.....	0.07 max.	18	8	
Nirosta 18-9.....	0.08-0.20	19	9	
35. Forging and Casting Corp., The, Fenn- dale, Mich.				
Fernite No. 1.....		15	65	
Fernite No. 2.....		15	35	
Fernite No. 3.....		12	24	
Fernite No. 4.....		28	22	
Fernite No. 5.....		21	12	
Fernite No. 6.....		18	8	
Fernite No. 7.....	Low	28		
Fernite No. 8.....		14		
Fernite No. 9.....	High	28		
Cyclops No. 17.....		8	18	Mn High
36. Frank Foundries Corp., Moline, Ill.				
Frankite Ni-Resist.....	0.80-3.00	1.50-2	14	6.00 Cu
Frankite "Copper-Free" Ni-Resist.....	2.70-3.00	2.50-3.50	20-22	
Frankite Ni-Hard.....	3.00-3.40	1.40-1.60	4-4.50	
Frankite High Chromium.....	1.00-2.00	22-34	3	
37. General Alloys Co., Boston				
Q Alloy A +.....	Depends on Service	15-19	66-68	
Q Alloy B.....	"	12	60	
X-ite.....	"	17-21	37-40	
X-B.....	"	15	35	
Economet.....	"	8-10	29-31	
Q Alloy CN1.....	"	24	12	
Q Alloy CN1-H.....	"	26-30	9-11	
Q Alloy CN2.....	"	17-19	8-10	
Q Alloy C1.....	"	17-19	0.50 min.	
Q Alloy C2.....	"	28-30	0.50 min.	
38. Halcomb Steel Div.,* Syracuse, N. Y.				
Grade A Stainless Steel Type 420....	0.35	13		
Grade B Stainless Steel Type 440....	0.60	17		
Grade B-100 Stainless Steel.....	0.95	17		
Stainless Iron #12 Type 410.....	0.12 max.	12		
Stainless Iron FM-2 Type 416.....	0.12 max.	13		Mo 0.50 max.
Stainless Iron #17 Type 430.....	0.12 max.	17		
Stainless Iron #20 Type 442.....	0.35 max.	20		
Stainless Iron #27 Type 446.....	0.35 max.	27		
Rezilal NCR238 Type 325.....	0.25 max.	8	23	Cu 1.25
Rezilal KA-2 Type 302.....	0.20 max.	18	8	
Rezilal FM-188 Type 303.....	0.20 max.	18	8	Mo 0.50
Rezilal 2-C Type 302-B.....	0.20 max.	18	8	Si 2.50
Rezilal #3 Type 309.....	0.20 max.	25	13	
Rezilal #4 Type 311.....	0.25 max.	20	25	
Rezilal #7 Type 310.....	0.25 max.	25	20	Si 1.50
39. Hawkrige Brothers Company, Boston (See Halcomb Steel Division)				
40. Haynes Stellite Co., Kokomo, Ind.				
Haynes Stellite No. 1.....		29-34		Co 43 min., W 11-14
Haynes Stellite No. 6.....		25-33		Co 55 min., W 3-6
Haynes Stellite No. 12.....		25-34		Co 47 min., W 7-10
Hascrome.....	0.80-1.20	10-14		Mn 3-5, Si 0.30-0.80
Hascrome.....	0.90-1.30	11-14		Mn 2-4, Si 0.50-1.00
Hastelloy A.....	Low			Mo 18-23
Hastelloy B.....	Low			Mo 24-33
Hastelloy C.....	Low	14-18		Mo 15-20, W 3-6
Hastelloy D.....	Low			Cu 2-4, Si 8-11
41. Hoskins Mfg. Co., Detroit				
Alloy No. 502.....	0.45-0.50	18-22	30-34	
Chromel-A.....		18-19	67-70	
Chromel-C.....		10-14	59-62	
Alloy No. 670.....		23-28	10-13	

(Continued)

*These trade names also used by Hawkrige Brothers Co., Boston.

	C	Cr	Ni	
42. Industrial Steels, Inc., Cambridge, Mass.				
Industrial 188	0.08-0.20	17-19	7-9	
Industrial 5188	0.08-0.20	17-19	7-9	Mo 0.20-0.30
Industrial 188-S	0.08 max.	17-19	7-9	
Industrial 199	0.08-0.20	18-20	8-10	
Industrial 199-S	0.08 max.	18-20	8-10	
Industrial 188-SMO	0.08 max.	17-19	7-11	Mo 2-4
Industrial 12	0.12 max.	11.50-13.50		
Industrial 12 T	0.12 max.	11.50-13		
Industrial 612	0.12 max.	11.50-13.50		Mo 0.20-0.30
Industrial 18	0.12 max.	18-18		
Industrial 35	0.30-0.35	13.50-14.50		
Industrial 65	0.60-0.70	16-17		
Industrial 100	0.90-1.00	17-18		
Industrial 7-MO	0.10 max.	25-30	3-5	Mo 1.50
43. Ingersoll Steel & Disc Co., Div. of Borg-Warner Corp., Chicago				
IngAclad (Stainless Clad)	0.11 max.	18-20	8-10	
IngAclad (Stainless Clad)	0.10 max.	17-20	8-12	Cb approx 1%
IngAclad (Stainless Clad)	0.10 max.	16-19	14 max.	Mo 2-4
44. International Nickel Co., Inc., New York				
A Nickel			99.40	
D Nickel			94-95	Mn 4-5
Inconel		13 00	79.5	Fe 6.5
K Monel			66	Cu 29, Al 2.75
Monel			67	Cu 30
Ni-Resist	2 75-3 10	2	14	Cu 6, Mn 1.25
Ni-Resist (Copper-Free)	2 75-3 10	2	20-30	Si 1.50
45. Jessop Steel Co., Washington, Pa.				
Hi-Gloss	0.20 max.	18	8	
Sta-Gloss	0.40	14		
Duro-Gloss C1	0.12 max.	15 max		
Duro-Gloss C2	0.12 max.	18		
Duro-Gloss C3	0.12 max.	23		
Duro-Gloss C4	0.12 max.	30		
Heat Resisting #4	0.20	12	24	
Heat Resisting #5	0.20	23	12	
46. Wm. Jessop & Sons, Inc., New York				
Corrosion Resistant "R-1"	0.15 max.	12	1 max.	
Corrosion Resistant "R-2"	0.28-0.32	12	1 max.	
Corrosion Resistant "R-3"	0.12 max.	18	11 max.	
Corrosion Resistant "R-4"	0.25	18	1	
47. Kay-Brunner Steel Products, Inc., Los Angeles				
Ni-Resist	2.75-3.10	1.50-4.00	13-15	Cu 0.80-1.00
48. Latrobe Electric Steel Co., Latrobe, Pa.				
Lesco L Stainless Iron	0.10 max.	11-13		
Lesco M Stainless Iron	0.10 max.	14-18		
Lesco H Stainless Iron	0.10 max.	18-20		
Lesco HH Stainless Iron	0.20 max.	23-30		
Lesco LS Stainless Iron	0.12 max.	11-13		S 0.20-0.30
(Free Machining)				Mo 0.30-0.50
Lesco 25-20 Stainless Iron	0.20 max.	24-26	18-20	
Lesco 25-12 Stainless Iron	0.20 max.	24-26	11-13	
Lesco 18-8 Se Stainless Iron	0.20 max.	17-20	7-10	
Regular Stainless	0.30-0.40	13-14		
Hy-Glo Stainless	0.60-0.70	16.50-18		
Lusterite Stainless	0.80-0.90	16.50-18		
49. Lebanon Steel Foundry, Lebanon, Pa.				
Circle "L" #10	0.20	5.50		Mo 0.55
Circle "L" #11	0.25	19		
Circle "L" #12	0.10	13		
Circle "L" #12-M	0.10	13		Se 0.25
Circle "L" #13	0.25	13		
Circle "L" #14	0.30	20		Cu 1
Circle "L" #15	0.30	27		
Circle "L" #22	0.07 max.	19.50	9	
Circle "L" #22-M	0.07 max.	19.50	9	Se 0.25
Circle "L" #22-XM	0.07 max.	19.50	9	Mo 3
Circle "L" #23	0.20 max.	19.50	9	
Circle "L" #23-M	0.20 max.	19.50	9	Se 0.25

(Continued)

	C	Cr	Ni	
49. Lebanon Steel Foundry, Lebanon, Pa.—Continued				
Circle "L" #23-XM	0.20 max.	19.50	9	Mo 3
Circle "L" #24	0.20 max.	19	19.50	
Circle "L" #25	0.20 max.	21	10	
Circle "L" #25-M	0.20 max.	21	10	Se 0.25
Circle "L" #30	0.20 max.	24	10	
Circle "L" #30-XM	0.20 max.	24	10	Mo 3
Circle "L" #31	0.25	28	11	
Circle "L" #32	0.50	75	35	
Circle "L" #34	0.07 max.	20	30	Mo 3.25, Cu 8 Si 3.25
Circle "L" #40	0.50 max	28	8	
Circle "L" #41	0.40	17	66.50	
Circle "L" #42	0.40	12	60	
Circle "L" #43	0.40	19	38	
Circle "L" #44	0.40	10	30	
Circle "L" #45	0.40	20	25	
Circle "L" #46	0.40	25	20	
Circle "L" #47	0.40	30	20	
Circle "L" #48	0.40	30	30	
50. Ludlum Steel Co.,* Watervliet, N. Y.				
Silchrome 18-8, Type 302.....	0.20 max	17.50-19	8-9	
Silchrome 18-8-B, Type 302-B.....	0.20 max	17.50-19	8-9	Si 2-3
Silchrome 18-8-EZ, Type 303.....	0.20 max	17.50-19	8-9	Se 0.20-0.30
Silchrome 18-8-S, Type 304.....	0.08 max.	17.50-19	8-9	
Silchrome 19-9, Type 305.....	0.20 max.	18-20	9-10	
Silchrome 19-9-S, Type 306.....	0.08 max.	18-20	9-10	
Silchrome 20-10, Type 307.....	0.20 max.	20-22	10-12	
Silchrome 20-10-S, Type 308.....	0.08 max.	20-22	10-12	
Silchrome 25-12, Type 309.....	0.20 max.	22-26	12-14	
Silchrome 25-20, Type 310.....	0.25 max.	24-26	19-21	
Silchrome 18-8-M, Type 316.....	0.10 max.	16-19	14 max.	Mo 2-4
Silchrome 18-8-T, Type 321.....	0.10 max.	17-20	7-10	Ti min. 4 x C
Silchrome 18-8-C, Type 347.....	0.10 max.	17-20	8-12	Cb 10 x C
Silchrome 12 Turbine Quality, Type 403	0.12 max	11.50-13		
Silchrome 12, Type 410.....	0.12 max	10-13.50		
Silchrome 12-2, Type 414.....	0.12 max	10-13.50	2.00 max.	
Silchrome 12-EZ, Type 416.....	0.12 max	12-14		S 0.40 max. Mo 0.65 max
Silchrome L-12, Type 420.....	0.30-0.40	12-14		
Silchrome 17, Type 430.....	0.12 max	14-18		
Silchrome RA, Type 434-A.....	0.12 max.	14-18		Si 1.00 Cu 1.00
Silchrome M-17, Type 440.....	0.60-0.70	14-18		
Silchrome H-17, Type 440.....	1.00-1.10	14-18		
Silchrome 21, Type 442.....	0.35 max	18-23		
Silchrome 28, Type 446.....	0.35 max.	23-30		
Silchrome 46M, Types 501 and 502.....	As specified	4-6		Mo 0.40-0.60
51. Michiana Products Corp., Michigan City, Ind.				
Fire Armor		20	65	
Fire Armor "B".....		12	60	
Zorite		15	37	
No. 48 Alloy.....		28	8	
No. 100 Alloy		25	12	
52. Michigan Steel Casting Co., Detroit				
Misco Metal	Depends on service	15	35	
Misco "C"	"	30	10	
Misco "B"	"	24	12	
Misco HN-1	"	15	65	
Misco HN-2	"	12	60	
Misco 18-8	"	18	8	
Misco 30-30	"	30	30	
Misco "N"	"	8	18	
Miscrome-1	"	18	3 max.	
Miscrome-3	"	28	3 max.	
53. Midvale Co., Nicetown, Philadelphia				
Midvaloy 1300-A	0.35	12.5		
Midvaloy 1300	0.10	12.5		
Midvaloy 1700	0.10	16.5		
Midvaloy 2100	0.10	20.5		
Midvaloy 2602	0.20	26.5	2	
Midvaloy HR-1	0.35	20	7	W 4
Midvaloy 18-08	0.10	18	9	

*See also the Allegheny Steel Co.

(Continued)

	C	Cr	Ni	
53. Midvale Co., Nicetown, Philadelphia—Continued				
Midvaloy 18-08 Se	0.10	18	9	Se 0.24
Midvaloy 25-10	0.18	24	11	
Midvaloy 25-10 B	0.55	23	11	
Midvaloy 25-20	0.13	25	19.5	Mo 0.18
Midvaloy Hy-X	0.50	8	22	Cu 1
Midvaloy 17-35	0.35	19	35	
Midvaloy ATV-1	0.35	11	36	
Midvaloy ATV-3	0.48	14	27	W 3.5
Midvaloy 976	0.47	9.7	1.5	Al 2.3
Midvaloy AMF	0.15		48	
Midvaloy BTG	0.30	11.5	60	W 2.5
53A. Milwaukee Steel Foundry Co.*				
54. National Alloy Steel Co., Blawnox, Pa.				
NA-1	0.10-0.50	28	10	
NA-2	0.10-0.50	15	35	
NA-4	0.10-0.50	18	8	
NA-4-M	0.10-0.50	18	8	Mo 3
NA-19	0.10-0.50	28		
NA-65	0.10-0.50	18	65	
55. National Forge & Ordnance Co., Irvine, Warren Co., Pa.				
Nationalloy 1	0.10-0.35	16-20	7-10	
Nationalloy 2	0.10-0.35	7-10	16-20	
Nationalloy 3	0.07-0.15	12-20		
56. National Tube Co., Pittsburgh. (See United States Steel Corp.)				
57. Ohio Steel Foundry Co., Lima, Ohio				
Fahrite N-6		15-19	65-68	
Fahrite N-5		10-14	59-62	
Fahrite N-1A		17-21	37-40	
Fahrite N-1		13-17	34-37	
Fahrite N-1B		8-12	29-32	
Fahrite N-10		18-22	24-27	
Fahrite N-4		6-10	17-20	
Fahrite N-8		31-35	3.0 max.	
Fahrite N-7		25-30	3.0 max.	
Fahrite N-9		16-24	3.0 max.	
Fahrite N-11		28-32	10-13	
Fahrite N-3A		26-30	7-9	
Fahrite N-12		23-27	19-21	
Fahrite N-3		23-28	10-13	
Fahrite N-3B		17-23	7-10	
Fahrite N-13		29-32	19-21	
Fahrite N-14		28-32	29-31	
Fahrite N-15		23-28	6-9	
Fahrite C-5		26-30	10-12	
Fahrite C-6		26-30	7-9	
Fahrite C-7		22-26	10-12	
Fahrite C-8		17-21	7-9	
Fahrite C-9		18-22	7-9	
Fahrite C-10		18-22	10-12	
Fahrite N-16		26-30	3.0 max.	
Fahrite N-17		16-20	3.0 max.	
Fahrite C-1		13-17	34-37	
Fahrite C-4		6-10	17-20	
Fahrite N-18	1.00-1.80	31-35	3.0 max.	
Fahrite N-19	Over 1.80	31-35	3.0 max.	
Fahrite N-20	1.00-1.80	25-30	3.0 max.	
Fahrite N-21	Over 1.80	25-30	3.0 max.	
Fahrite N-22	1.00-1.80	16-24	3.0 max.	
Fahrite N-23	Over 1.80	16-24	3.0 max.	
58. Otis Elevator Co., Buffalo, N. Y.				
O-18	0.10 max.	18-20	8-10	
O-12	0.10-0.15	12-16		
O-16	0.10-0.15	15-18		
O-24	0.20 max.	20-30	10-20	
O-30	0.25 max.	26-30		
36-N	0.25 max.	14-16	33-36	
O-8	0.15-0.26	8.5-10 5		Mo 1.25-1.75
O-4	0.15-0.35	4-8		Mo 0.25-2.0
59. Pacific Foundry Co., Ltd., San Francisco				
Corrosiron				Si 14.40-14.75
Pyrocast		22-27	1-22	

*See last page of this article for these trade names.

(Continued)

	C	Cr	Ni	
60. Page Steel & Wire Div., American Chain & Cable Co., Inc., Monessen, Pa.				
Page-Allegheny C	0.08-0.20	17.50-19	8-9	
Page-Allegheny Free Machining Quality	0.20 max.	17.50-19	8-9	S or Se 0.07 min. or Mo 0.60 max.
Page-Allegheny A	0.08 max.	17.50-19	8-9	
Page-Allegheny B	0.08-0.20	18-20	9-10	
Page-Allegheny B Special	0.08 max.	18-20	9-10	
Page-Allegheny #22	0.08-0.20	20-22	10-12	
Page-Allegheny #22 Special	0.08 max.	20-22	10-12	
Page-Allegheny #44	0.20 max.	22-26	12-14	
Page-Allegheny 2520	0.25 max.	24-26	19-21	
Page-Allegheny #33 Turbine Quality	0.12 max.	11.50-13		
Page-Allegheny Ohmaloy	0.12 max.	12-14		Al 4.00-4.50
Page-Allegheny #33 Nonhardening Quality	0.08 max.	11 50-13.50		Al 0.10-0.20
Page-Allegheny #33	0.12 max.	10-13.50		
Page-Allegheny #33 Free Machining Quality	0.12 max.	12-14		S or Se 0.07 min. or Mo 0.60 max.
Page-Allegheny #66	0.12 max.	14-18		
Page-Allegheny #67	0.35 max.	18-23		
Page-Allegheny #55	0.35 max.	23-30		
Page-Allegheny Electric Metal (Nicalor)			45-49	
Page-Allegheny Metal AMO	0.10 max.	16-19	0.14 max.	Mo 2-4
Page-Allegheny Metal ATI	0.10 max.	17-20	7-10	Ti 4 x C
Page-Allegheny Metal BTI	0.20 max.	18-20	8-10	Ti 4 x C
Page-Allegheny Metal with Colum- bium	0.10 max.	17-20	8-12	Cb 10 x C
Page-Allegheny #46	Over 0.10	4-6		
Page-Allegheny #46	0.10 max.	4-6		
61. Pioneer Alloy Products Co., Cleveland				
Pioneer Acid Resisting	0.25	25	35	Mo 5
Pioneer Heat Resisting	0.50	20	20	Mo 1
Pioneer 18- 8	0.20	18	8	
Pioneer 24-12	0.20	24	12	
Pioneer 28-10	0.25	28	10	
Pioneer 28- 3	0.25	28	3	
62. Poldi Steel Works, New York				
Poldi AK-1	0.10	13		
Poldi AK-2	0.20	16		
Poldi AK-5	0.50	15 5		Mo 0.40
Poldi AK-H	1.00	16		Mo 1, Co 1.3
63. George W. Prentiss & Co., Holyoke, Mass.				
Vac-Melt B7M		15	60	Mo 7, Mn 2
64. Republic Steel Corp., Cleveland				
Enduro 18-8	0.08-0.20	17.50-19	8-9	
Enduro 18-8-B	0.08-0.20	17.50-19	8-9	Si 2-3
Enduro 18-8-FM	0.20 max.	17.50-19	8-9	S, Se 0.07 min. or Mo 0.60 max.
Enduro 18-8-S	0.08 max.	17.50-19	8-9	
Enduro 19-9	0.08-0.20	18-20	9-10	
Enduro 19-9-S	0.08 max.	18-20	9-10	
Enduro HCN	0.20 max.	22-26	12-14	
Enduro NC-3	0.25 max.	24-26	19-21	
Enduro 18-8-S-Mo	0.10 max.	16-19	14 max.	Mo 2-4
Enduro 19-9-S-Ti	0.10 max.	17-20	7-10	Ti 4 x C
Enduro "S" Turbine Quality	0.12 max.	11.50-13		
Enduro S-1	0.12 max.	10-13.50		
Enduro FC	0.12 max.	12-14		S, Se 0.07 min. or Mo 0.60 max.
Enduro "S" Hi Car.	Over 0.12	12-14		
Enduro AA	0.13 max.	14-18		
Enduro AA Hi Car.	Over 0.12	14-18		
Enduro HC	0.35 max.	23-30		
Enduro 4-6	0.10 min.	4-6		
Enduro 4-6	0.10 max.	4-6		
Enduro 20-10	0.08-0.20	20-22	10-12	
Enduro 20-10-S	0.08 max.	20-22	10-12	
Enduro 18-8-SCB	0.10 max.	17-20	8-12	Cb 10 x C
Enduro 17-7	0.10-0.20	16-17 50	7-8.50	

(Continued)

	C	Cr	Ni	
65. Rustless Iron and Steel Corp., Baltimore, Md.				
Rustless 17-7	0.10-0.20	16-17.50	7-8.50	
Defstain	0.08-0.20	17.50-19	8-9	
Defstain-Machining	0.20 max.	17.50-19	8-9	Plus S
Defstain	0.08 max.	17.50-19	8-9	
Special Defstain	0.08-0.20	18-20	9-10	
Special Defstain	0.08 max.	18-20	9-10	
Rustless 20-10	0.08-0.20	20-22	10-12	
Rustless 20-10	0.08 max.	20-22	10-12	
Rustless 25-12	0.20 max.	22-26	12-14	
Rustless 29-9	0.25 max.	27-31	8-10	
Defrust, Turbine Quality	0.12 max.	11 50-13		
Defrust	0.12 max.	10-13.50		
Defrust-N	0.12 max.	10-13 50	2 00 max.	
Defrust-Machining ..	0.12 max.	12-14		Plus S
Rustless 13 HC 35	0.40 max.	12-14		
Rustless 17	0.12 max.	14-18		
Rustless 17 FM	0.12 max.	14-18		Plus S
Rustless 17 HC 60	0.60-0.70	14-18		
Rustless 17 HC 90	0.90-1.00	14-18		
Rustless 21	0.35 max.	18-23		
Deheat ..	0.35 max.	23-30		
66. Sharon Steel Corp., Sharon, Pa.				
Sharon Stainless Type 301X	0.10-0.20	16-17.50	7-8.50	
Sharon Stainless Type 302	0.08-0.20	17.50-19	8-9	
Sharon Stainless Type 302B	0.08-0.20	17.50-19	8-9	Si 2-3
Sharon Stainless Type 303 ..	0.20 max.	17.50-19	8-9	S or Se 0.07 min or Mo 0.60 max
Sharon Stainless Type 304	0.08 max.	17.50-19	8-9	
Sharon Stainless Type 305 ..	0.08-0.20	18-20	9-10	
Sharon Stainless Type 306 ..	0.08 max.	18-20	9-10	
Sharon Stainless Type 307 ..	0.08-0.20	20-22	10-12	
Sharon Stainless Type 308 ..	0.08 max.	20-22	10-12	
Sharon Stainless Type 309 ..	0.20 max.	22-26	12-14	
Sharon Stainless Type 310 ..	0.25 max.	24-26	19-21	
Sharon Stainless Type 311 ..	0.25 max.	19-21	24-26	
Sharon Stainless Type 316 ..	0.10 max.	16-19	14 max.	Mo 2-4
Sharon Stainless Type 321 ..	0.10 max.	17-20	7-10	Ti Min. 4 x C
Sharon Stainless Type 325 ..	0.25 max.	7-10	19-23	Cu 1-1.50
Sharon Stainless Type 327 ..	0.25 max.	25-30	3-5	
Sharon Stainless Type 343 ..	0.25	12-16	12-16	W3
Sharon Stainless Type 347 ..	0.10 max.	17-20	8-12	Cb 10 x C
Sharon Stainless Type 403 ..	0.12 max.	11 50-13		
Sharon Stainless Type 405 ..	0.08 max.	11 50-13 50		Al 0.10-0.20
Sharon Stainless Type 408 ..	0.12 max.	12-14		Al 4-4.50
Sharon Stainless Type 410 ..	0.12 max.	10-13 50		
Sharon Stainless Type 414 ..	0.12 max.	10-13 50	2 00 max.	
Sharon Stainless Type 416 ..	0.12 max.	12-14		S or Se 0.07 min or Mo 0.60 max
Sharon Stainless Type 420 ..	Over 0.12	12-14		
Sharon Stainless Type 430 ..	0.12 max.	14-18		
Sharon Stainless Type 430F ..	0.12 max.	14-18		S or Se 0.07 min or Mo 0.60 max
Sharon Stainless Type 431 ..	0.15 max.	14-18	2.00 max.	Si 1, Cu 1
Sharon Stainless Type 434A ..	0.12 max.	14-18		
Sharon Stainless Type 440 ..	Over 0.12	14-18		
Sharon Stainless Type 441 ..	Over 0.15	14-18	2 00 max	
Sharon Stainless Type 442 ..	0.35 max.	18-23		
Sharon Stainless Type 446 ..	0.35 max.	23-30		
Sharon Stainless Type 501 ..	Over 0.10	4-6		
Sharon Stainless Type 502 ..	0.10 max.	4-6		
67. Shawinigan Chemicals, Ltd., Montreal, Que.				
Acid Resisting Shawinigan KA-2	0.12 max.	16-23	7-11	
Acid Resisting Shawinigan KA-2-Mo ..	0.12 max.	16-23	7-11	
Heat Resisting Shawinigan HR-1	0.25-0.35	24-30	12-18	
Heat Resisting Shawinigan HR-2 ..	0.36-0.50	16-23	31-39	
68. Silyer Steel Casting Co., Milwaukee				
Silyer 60	0.10	18.5	9	Si 1
Silyer 62	0.18	24.5	12.5	Si 1
Silyer 64	0.25	30	9.5	Si 1
Silyer 66	0.10	13		Si 1
Silyer 67	0.25	17		Si 1
Silyer 70	0.45	15	35	Si 1

(Continued)

	C	Cr	Ni
69. Standard Alloy Co., Inc., Cleveland			
H.R. #1		20	20
H.R. #2		20	25
H.R. #3		17	37
H.R. #4		15	60
H.R. #5		25	20
H.R. #6		25	12
H.R. #7		18	8
H.R. #8		28-30	
H.R. #9		18	
70. Superior Steel Corp., Pittsburgh			
Superior Silcrome Type 301-X	0.10-0.20	16-17.50	7-8.50
Superior Silcrome Type 302	Over 0.08-0.20	17.50-19	8-9
Superior Silcrome Type 304	0.08 max.	17.50-19	8-9
Superior Silcrome Type 305	Over 0.08-0.20	18-20	9-10
Superior Silcrome Type 306	0.08 max.	18-20	9-10
Superior Silcrome Type 410	0.12 max.	10-13.50	
Superior Silcrome Type 414	0.12 max.	10-13.50	2.00 max.
Superior Silcrome Type 430	0.12 max.	14-18	
71. Taylor-Wharton Iron & Steel Co., High Bridge, N. J.			
Tisco 53	0.15-0.35	4-6	Mo 0.40-0.65 W 0.80-1.25 Mn 1 max. Si 2 max.
Tisco 101	0.16 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 101A*	0.16 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 102	0.07 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 102A*	0.07 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 103	0.20 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 103A*	0.20 max.	16.5-20	7-10.5 Mn 1 max. Si 2 max.
Tisco 104	0.16 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 104A*	0.16 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 105	0.07 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 105A*	0.07 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 106	0.20 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 106A*	0.20 max.	18-22	7-10.5 Mo 2-4 Mn 1 max. Si 2 max.
Tisco 107	0.30 max.	26-30	8-12 Mn 1 max. Si 0.5-1.5
Tisco 108	0.20 max.	23-27	17-21 Mn 1 max. Si 2 max.
Tisco 109	0.20 max. Cr	22-26	18-22 Mn 0.50-0.75 Si 1.50 max.
Tisco 110	max. 1.00	20 min.	9 min. Mn 1 max. Si 2 max.
Tisco 120	0.50 max.	15-18	35-40 Mn 1 max. Si 2 max.
Tisco 130	0.10 max.	26-30	Mn 0.40-0.60 Si 2 max.
Tisco 131	0.10 max.	16-18	Mn 0.40-0.60 Si 2 max.
Tisco 132	0.10 max.	11.5-16	Mn 0.40-0.60 Si 2 max.
Tisco 160	2.50-3.50	1.50-4	12-15 Mn 1-1.50 Si 1.25-2 Cu 5-7
72. Thomas Steel Co., Warren, Ohio			
Stainless Steel		16-18	8

(Continued)

*These alloys contain 0.20-0.30% Se.

	C	Cr	Ni	
73. Timken Roller Bearing Co., Canton, Ohio				
Timken Carbon Moly	0 10-0 20			Mo 0.45-0.65
Timken Silmo	0.15 max.			Si 1.15-1.65.
				Mo 0.45-0.65
Timken DM	0.15 max.	1.00-1.50		Si 0.50-1,
				Mo 0.45-0.65
Timken DM 2	0.15 max.	0.80-1.10		Mo 0.45-0.65
Timken Sicromo 1	0.15 max.	0.75-1.25		Si 1-1.40,
				Mo 0.45-0.65
Timken Sicromo 2	0.15 max.	1.75-2.25		Si 1-1.40,
				Mo 0.45-0.65
Timken Sicromo 2½	0.15 max.	2.25-2.75		Si 0.50-1,
				Mo 0.45-0.65
Timken Sicromo 3	0.15 max.	2.75-3.25		Si 1-1.40,
				Mo 0.45-0.65
Timken Sicromo 5	0.15 max.	4-6		Si 1-2,
				Mo 0.45-0.65
Timken 5% Chrome Moly	0.15 max.	4-6		Si 0.50 max.,
				Mo 0.45-0.65
Timken 18-8 Stainless	0 07 max.	17-20	8-10	Si 0.75 max
74. Uddeholm Co. of America, Inc., New York				
UHB Stainless 1	0 08	13 5		
UHB Stainless 21	0.07 max.	14.7		
UHB Stainless 31	0 18	13 5	0 60	
UHB Stainless 2	0.10	17.5		Si 1 00
UHB Stainless 22	0 15	16.7	1.5	
UHB Stainless 3 MM	0.06 max	18 0	8.5	
UHB Stainless 3 M	0.06-0.09	18 0	8 3	
UHB Stainless 3	0.09-0.12	18 0	8 0	
UHB Stainless 3 H	0 12	18 0	8 0	
UHB Stainless 33	0 08	14 5	13.0	
UHB Stainless 4 MM	0.06 max.	17.5	9.5	Mo 1 4
UHB Stainless 43	0 08	18 0	8 0	Se 0 20, Mn 1.00
UHB Stainless 4 M	0 06-0.09	17 5	9 3	Mo 1.4
UHB Stainless 4	0.09-0.12	17 5	9 0	Mo 1.4
UHB Stainless 14	0 06	19.0	9.0	Mo 1.5, Mn 0.75
				Si 0 50
UHB Stainless 24	0 06	17.0	10 5	Mo 2.5, Mn 0.80
UHB Stainless 44	0 10	25 0	5 0	Mo 1.7
UHB Stainless 5	0 20	25.0		Si 1, Mn 0.50
UHB Stainless 25	0 07	23.5	21.5	Si 1.5, Mn 1
UHB Stainless 6	0 30	13.5		
UHB Stainless 16	0.27	13 5		Mo 1.3
UHB Stainless 26	0 50	14 0		
AEB	0.95	14 0		Si 0 15, Mn 1
UHB Uddco 1	0.15	5 0		
UHB Uddco 2	0.15	5 0		Mo 0 50
75. United States Steel Corp.* New York				
USS 18-8 Type 302	0 08-0 20	17 5-19	8-9	
USS 18-8 FM Type 303	0 20 max.	17.5-19	8-9	S or Se 0 07 min.
				or Mo 0 60 max.
USS 18-8 S Type 304	0 08 max.	17.5-19	8-9	
USS 19-9 Type 305	0 08-0.20	18-20	9-10	
USS 19-9 S Type 306	0 08 max.	18-20	9-10	
USS 20-10 Type 307	0.08-0.20	20-22	10-12	
USS 20-10 S Type 308	0 08 max.	20-22	10-12	
USS 25-12 Type 309	0.20 max.	22-26	12-14	
USS 25-20 Type 310	0.25 max.	24-26	19-21	
USS 18-8 Mo Type 316	0.10 max.	16-19	14 max	Mo 2-4
USS 18-8 Ti Type 321	0 10 max.	17-20	7-10	Ti min. 4 x C
USS 18-8 Cb Type 347	0 10 max.	17-20	8-12	Cb 10 x C
USS 12 Turbine Type 403	0.12 max.	11.5-13		
USS 12 Type 410	0.12 max.	10-13.5		
USS 12 FM Type 416	0.12 max.	12-14		S or Se 0 07 min.
				or Mo 0.60 max.
USS 17 Type 430	0.12 max.	14-18		
USS 21 Type 442	0.35 max.	18-23		
USS 27 Type 446	0.35 max.	23-30		
USS 5 Type 501	0.10 min.	4-6		
USS 5 S Type 502	0.10 max.	4-6		

(Continued)

*These trade names are also used by American Steel & Wire Co., Cleveland; Carnegie-Illinois Steel Corp., Pittsburgh; and National Tube Co., Pittsburgh.

	C	Cr	Ni	
76. Universal-Cyclops Steel Corp.,* Titusville, Pa.				
Cyclops No. 17-A.....	0 40	8	20	
Cyclops No. 17-B.....	0 20	8	20	
Cyclops K Rustless.....	0 60	8		W 8
Uniloy 1409.....	0 10	13		
Uniloy 1409-M.....	0 10	13 5		Mo 0 40
Uniloy 1809.....	0 10	17		
Uniloy 2825.....	0 25	28		
Uniloy 1435 (Stainless A).....	0 35	13		
Uniloy 1860 (Stainless B).....	0 60	17		
Uniloy Special 18-8.....	0 15	18	8	
Uniloy Special 18-8-S.....	0 07	18	8	
Uniloy Special 18-8-M.....	0 15	18	8	Se 0.25
Uniloy Special 21-12.....	0 20	21	12	
Uniloy Special 24-11.....	0 20	24	11	
Uniloy Special 25-20.....	0 20	25	20	
Uniloy Special 15-35.....	0 25	15	35	
77. Universal Steel Div., Bridgeville, Pa. (See Universal-Cyclops Steel Corp.)				
78. Vanadium-Alloy Steel Co.,** Latrobe, Pa.				
Stainless "A".....	0 35	13 50		
Stainless "B".....	0 65	16 5		
Stainless "T".....	0 12 max	13.5		
Stainless F.M.S.....	0 12 max	13.5		S 0.30
Stainless C2.....	0 12 max.	17		
Stainless C2F.....	0 12 max.	17		S 0 30
Colonial 410.....	0 12 max.	13.5	1	
Colonial 410F.....	0 12 max.	13.5	1	S 0 30
Colonial 610.....	0 12 max.	17	1	
Colonial 610F.....	0 12 max.	17	1	S 0 30
Colonial 795.....	1	17.5	1	
Stainless "N".....	0 15 max.	18	9	
79. Vulcan Crucible Steel Co., Alliquippa, Pa.				
Stainless Type "A".....	0 12 min	9-16		
Stainless Iron Type C-2.....	0 12 max.	15 max		
80. Warman Steel Casting Co., Los Angeles				
Warman 5.....	0 18 min	4-7		
Warman 5M.....	0 18 min	4-7		Mo 0 5-0 7
Warman 13.....	0 12 min	11-14		
Warman Calduro 13-2.....	0 20 min.	12 5-15	1.5-2.5	
Warman Calmar 18-8.....	0 16 min	17-20	7-10	
Warman Calmar 18-8M.....	0 16 min.	17-20	7-10	Mo 3-4.5
Warman Calmar 18-8 Cb.....	0 16 min	17-20	7-10	Cb 8 to 10 x C
Warman Caloxo 18.....	0 16 min.	16-20		
Warman Caloxo 18-2.....	0 20 min.	16-20	1.5-2.5	
Warman Caloxo 26.....	0 25 min	25-30		
Warman Caloxo 25-20.....	0 20 min.	23-27	17-21	
Warman Caloxo 25-20M.....	0 20 min.	23-27	17-21	Mo 3-4.5
Warman Caloxo 28-10.....	0 25 min.	27-30	8-12	
Warman Caloxo 28-10M.....	0 25 min	27-30	8-12	Mo 3-4.5
Warman Caloxo 26-4.....	0 25 min	25-30	2.5-4	
Warman Caloxo 8-18.....	0 16 min.	7-10	17-20	
Warman Caloxo 15-25.....	0 20 min	14-17	23-27	
Warman Caloxo 15-25M.....	0 20 min	14-17	23-27	Mo 3-4.5
Warman Caloxo 15-35.....	0 20 min	14-17	33-37	
81. Webb Wire Works, The, New Brunswick, N. J.				
Ship Brands				
Blue Label.....	0 10	13.5	2	
Red Label.....	0 30	14.5		
Orange Label.....	0 09	18	8	
82. West Leechburg Steel Co., Pittsburgh (See Allegheny Steel Co.)				

(Continued)

*These trade names also used by Universal Steel Div., Bridgeville, Pa.

**These trade names are also used by Colonial Steel Div., Pittsburgh.

	C	Cr	Ni
83. Wheelock, Lovejoy & Co., Inc., Cambridge, Mass.			
Whelco "A"	0 12 max	13.5	
Whelco "B"	0 15	18	8
Whelco #1	0 12 max	12.5	
Whelco #2	0 15	18	8
Whelco #3	0 30	9	19
Whelco #4	0 12 max.	17	
Whelco #5	0 11	21	
Whelco #6	0 40	13.5	
Whelco #7	0 65	17	
Whelco #8	1 15	18	
Whelco #9	0 35 max.	28	
84. Wickwire Spencer Steel Co., New York			
Wissco 1	0 12 max	10-13.5	
Wissco 1M	0 12 max.	12-14	S, Se or Mo
Wissco 2	0 12 min.	12-14	
Wissco 3	0 12 max.	14-18	
Wissco 4	0 08-0 20	17.5-19	8-9
Wissco 4M	0 20 max.	17.5-19	8-9
Wissco 4S	0 08 max.	17.5-19	8-9
Wissco 5A	0 20 max.	22-26	12-14
Wissco 5CN	0 25 max.	19-21	24-26
			Mn and Si

Trade Names of Corrosion and Heat Resisting Alloys

(Alphabetically Arranged)

The number preceding each trade name indicates the manufacturer listed in the first section of this compilation. The approximate composition of the important alloying elements is also given with the trade name under the manufacturer.

<p>A</p> <p>44. A Nickel</p> <p>22. A R. Stainless</p> <p>67. Acid Resisting Shawinigan KA-2 and KA-2-Mo</p> <p>3. Acme</p> <p>1. Acme Stainless Type 410, 430, 301-X, 302, 304</p> <p>74. AEB</p> <p>29. Alcumite</p> <p>2. Allegheny Brands</p> <p>41. Alloy No. 502</p> <p>41. Alloy No. 670</p> <p>4. Amsco Alloy Brands</p> <p>12. Anka H, M, and O</p> <p>12. Arcanka</p> <p>5. Armco Brands</p> <p>B</p> <p>12. B B</p> <p>12. BB4K</p> <p>7. B & W Brands</p> <p>9. Bethadur Brands</p> <p>9. Bethalon 303</p> <p>9. Bethalon 416</p> <p>8. Bethlehem Tantiron</p> <p>81. Blue Label</p> <p>10. Braeburn Stainless</p> <p>11. Brearley-A, B, and K</p> <p>C</p> <p>15. Calite Brands</p> <p>26. Chromax</p> <p>25. Chrome-Nickel A and B</p> <p>41. Chromel A and C</p> <p>26. Cimex</p> <p>49. Circle "L" Brands</p> <p>24. Cobaltchrom (Stainless)</p> <p>78. Colonial Brands</p> <p>21. Cooper Brands</p> <p>46. Corrosion Resistant "R-1", "R-2", "R-3" and "R-4"</p> <p>59. Corroiron</p> <p>7. Croloy Brands</p> <p>27. Cromin "D"</p> <p>27. Cupron</p> <p>35. Cyclops No. 17</p>	<p>C</p> <p>76. Cyclops No. 17-A and No. 17-B</p> <p>76. Cyclops K Rustless</p> <p>D</p> <p>44. D Nickel</p> <p>65. Defheat</p> <p>65. Defrust</p> <p>65. Defrust-Machining</p> <p>65. Defrust N</p> <p>65. Defrust, Turbine Quality</p> <p>65. Defstain</p> <p>65. Defstain-Machining</p> <p>28. Duraloy Brands</p> <p>29. Durco Brands</p> <p>29. Durichlor</p> <p>29. Durimet</p> <p>29. Duriron</p> <p>45. Duro-Gloss C1, C2, C3 and C4</p> <p>E</p> <p>37. Economet</p> <p>32. EM Brands</p> <p>64. Enduro Brands</p> <p>12. Engineering</p> <p>30. Esco Alloy 36, 40, 43 and 45</p> <p>3. Excelsior</p> <p>F</p> <p>33. F Brands</p> <p>57. Fahrte Brands</p> <p>35. Fernite Brands</p> <p>51. Fire Armor</p> <p>51. Fire Armor "B"</p> <p>36. Frankite "Copper-Free" Ni-Resist</p> <p>36. Frankite High Chromium</p> <p>36. Frankite Ni-Hard</p> <p>36. Frankite Ni-Resist</p> <p>G</p> <p>38. Grade A Stainless Steel Type 420</p> <p>38. Grade B Stainless Steel Type 440</p> <p>38. Grade B-100 Stainless Steel</p>	<p>H</p> <p>69. H. R. Brands</p> <p>40. Hascrome</p> <p>40. Hastelloy A, B, C and D</p> <p>40. Haynes Stellite No. 1, 6 and 12</p> <p>45. Heat Resisting 24 and 25</p> <p>67. Heat Resisting Shawinigan HR-1 and HR-2</p> <p>45. Hi-Gloss</p> <p>48. Hy-Glo Stainless Steel</p> <p>I</p> <p>13. Illium G and R</p> <p>44. Inconel</p> <p>42. Industrial Brands</p> <p>43. IngAlcad</p> <p>11. Inventor</p> <p>K</p> <p>44. K Monel</p> <p>L</p> <p>48. Lesco Brands</p> <p>23. LO-CRO 46, 46 MO and 46 W</p> <p>11. Lowscore</p> <p>48. Lusterite Stainless Steel</p> <p>M</p> <p>21. Monel</p> <p>44. Monel</p> <p>53. Midvaloy Brands</p> <p>52. Misco Brands</p> <p>52. Miscrome 1 and 3</p> <p>N</p> <p>58. 36 N</p> <p>54. NA Brands</p> <p>22 N.C. Heat Resisting</p> <p>58. Nationalloy 1, 2 and 3</p> <p>26. Nichrome wire, castings, "S" and V</p> <p>21. Nickel</p> <p>44. Ni-Resist</p> <p>47. Ni-Resist</p>
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(Continued)

*Firms using "Stainless", "Stainless Iron", "Stainless Steel" or "Stainless Type" with letters or numbers for their trade names are as follows: 3, 17, 25, 34, 38, 72, 78 and 79.

53A. Milwaukee Steel Foundry Co., Milwaukee

Location	C	Cr	Ni	Mo
Millwaukee 18-8	0.18 max.	17-19	7-9	...
Millwaukee 18-8-S	0.07 max.	17-19	7-9	...
Millwaukee 18-8SMO	0.07 max.	17-19	7-9	3-4
Millwaukee 29-9	0.25 max.	28-30	8-10	...

Decimal and Metric Equivalents of Parts of an Inch

In.	In.	Mm.	In.	In.	Mm.
$\frac{1}{16}$	= 0.015625	= 0.39687	$\frac{33}{64}$	= 0.515625	= 13.09671
$\frac{1}{8}$	= 0.03125	= 0.79374	$\frac{17}{32}$	= 0.53125	= 13.49362
$\frac{3}{16}$	= 0.046875	= 1.19061	$\frac{9}{16}$	= 0.546875	= 13.89045
$\frac{1}{4}$	= 0.0625	= 1.58748	$\frac{5}{8}$	= 0.5625	= 14.28737
$\frac{5}{16}$	= 0.078125	= 1.98435	$\frac{31}{64}$	= 0.578125	= 14.68419
$\frac{3}{8}$	= 0.09375	= 2.38123	$\frac{19}{32}$	= 0.59375	= 15.08111
$\frac{7}{16}$	= 0.109375	= 2.77809	$\frac{31}{64}$	= 0.609375	= 15.47793
$\frac{1}{2}$	= 0.125	= 3.17497	$\frac{3}{4}$	= 0.625	= 15.87485
$\frac{5}{8}$	= 0.140625	= 3.57183	$\frac{13}{16}$	= 0.640625	= 16.27167
$\frac{3}{4}$	= 0.15625	= 3.96871	$\frac{27}{32}$	= 0.65625	= 16.66859
$\frac{7}{8}$	= 0.171875	= 4.36557	$\frac{11}{8}$	= 0.671875	= 17.06541
$\frac{15}{16}$	= 0.1875	= 4.76245	$\frac{7}{4}$	= 0.6875	= 17.46234
$\frac{1}{2}$	= 0.203125	= 5.15931	$\frac{141}{128}$	= 0.703125	= 17.85915
$\frac{1}{8}$	= 0.21875	= 5.55620	$\frac{45}{64}$	= 0.71875	= 18.25608
$\frac{1}{4}$	= 0.234375	= 5.95305	$\frac{47}{64}$	= 0.734375	= 18.65289
$\frac{1}{4}$	= 0.25	= 6.34994	$\frac{3}{4}$	= 0.75	= 19.04982
$\frac{1}{4}$	= 0.265625	= 6.74679	$\frac{49}{64}$	= 0.765625	= 19.44663
$\frac{1}{2}$	= 0.28125	= 7.14368	$\frac{51}{64}$	= 0.78125	= 19.84356
$\frac{1}{2}$	= 0.296875	= 7.54053	$\frac{21}{16}$	= 0.796875	= 20.24037
$\frac{1}{8}$	= 0.3125	= 7.93743	$\frac{11}{8}$	= 0.8125	= 20.63731
$\frac{1}{4}$	= 0.328125	= 8.33427	$\frac{53}{64}$	= 0.828125	= 21.03411
$\frac{1}{2}$	= 0.34375	= 8.73117	$\frac{55}{64}$	= 0.84375	= 21.43105
$\frac{5}{8}$	= 0.359375	= 9.12801	$\frac{57}{64}$	= 0.859375	= 21.82785
$\frac{3}{8}$	= 0.375	= 9.52491	$\frac{7}{8}$	= 0.875	= 22.22479
$\frac{5}{8}$	= 0.390625	= 9.92175	$\frac{59}{64}$	= 0.890625	= 22.62159
$\frac{1}{2}$	= 0.40625	= 10.31865	$\frac{61}{64}$	= 0.90625	= 23.01853
$\frac{5}{8}$	= 0.421875	= 10.71549	$\frac{39}{32}$	= 0.921875	= 23.41533
$\frac{1}{4}$	= 0.4375	= 11.11240	$\frac{11}{8}$	= 0.9375	= 23.81228
$\frac{5}{8}$	= 0.453125	= 11.50923	$\frac{63}{64}$	= 0.953125	= 24.20907
$\frac{1}{2}$	= 0.46875	= 11.90614	$\frac{71}{64}$	= 0.96875	= 24.60602
$\frac{3}{4}$	= 0.484375	= 12.30297	$\frac{65}{64}$	= 0.984375	= 25.00281
$\frac{1}{2}$	= 0.5	= 12.69988	1	= 1.	= 25.4

Decimal Inch Equivalents of Millimeters and Fractions of Millimeters*

Mm.	In.	Mm.	In.	Mm.	In.	Mm.	In.
1/50	0.000 787	46/50	0.036 220	9	0.354 33	18	0.708 66
2/50	0.001 575	47/50	0.037 008	9.2	0.362 20	18.2	0.716 53
3/50	0.002 362	48/50	0.037 795	9.4	0.370 08	18.4	0.724 41
4/50	0.003 150	49/50	0.038 583	9.6	0.377 95	18.6	0.732 28
5/50	0.003 937			9.8	0.385 83	18.8	0.740 16
6/50	0.004 724	1	0.039 37	10	0.393 70	19	0.748 03
7/50	0.005 512	1.2	0.047 24	10.2	0.401 57	19.2	0.755 90
8/50	0.006 299	1.4	0.055 12	10.4	0.409 45	19.4	0.763 78
9/50	0.007 087	1.6	0.062 99	10.6	0.417 32	19.6	0.771 65
10/50	0.007 874	1.8	0.070 87	10.8	0.425 20	19.8	0.779 53
11/50	0.008 661	2	0.078 74	11	0.433 07	20	0.787 40
12/50	0.009 449	2.2	0.086 61	11.2	0.440 94	20.2	0.795 27
13/50	0.010 236	2.4	0.094 49	11.4	0.448 82	20.4	0.803 15
14/50	0.011 024	2.6	0.102 36	11.6	0.456 69	20.6	0.811 02
15/50	0.011 811	2.8	0.110 24	11.8	0.464 57	20.8	0.818 90
16/50	0.012 598	3	0.118 11	12	0.472 44	21	0.826 77
17/50	0.013 386	3.2	0.125 98	12.2	0.480 31	21.2	0.834 64
18/50	0.014 173	3.4	0.133 86	12.4	0.488 19	21.4	0.842 52
19/50	0.014 961	3.6	0.141 73	12.6	0.496 06	21.6	0.850 39
20/50	0.015 748	3.8	0.149 61	12.8	0.503 94	21.8	0.858 27
21/50	0.016 535	4	0.157 48	13	0.511 81	22	0.866 14
22/50	0.017 323	4.2	0.165 35	13.2	0.519 68	22.2	0.874 01
23/50	0.018 110	4.4	0.173 23	13.4	0.527 56	22.4	0.881 89
24/50	0.018 898	4.6	0.181 10	13.6	0.535 43	22.6	0.889 76
25/50	0.019 685	4.8	0.188 98	13.8	0.543 31	22.8	0.897 74
26/50	0.020 472	5	0.196 85	14	0.551 18	23	0.905 51
27/50	0.021 260	5.2	0.204 72	14.2	0.559 05	23.2	0.913 38
28/50	0.022 047	5.4	0.212 60	14.4	0.566 93	23.4	0.921 26
29/50	0.022 835	5.6	0.220 47	14.6	0.574 80	23.6	0.929 13
30/50	0.023 622	5.8	0.228 35	14.8	0.582 68	23.8	0.937 01
31/50	0.024 409	6	0.236 22	15	0.590 55	24	0.944 88
32/50	0.025 197	6.2	0.244 09	15.2	0.598 42	24.2	0.952 75
33/50	0.025 984	6.4	0.251 97	15.4	0.606 30	24.4	0.960 63
34/50	0.026 772	6.6	0.259 84	15.6	0.614 17	24.6	0.968 50
35/50	0.027 559	6.8	0.267 72	15.8	0.622 05	24.8	0.976 38
36/50	0.028 346	7	0.275 59	16	0.629 92	25	0.984 25
37/50	0.029 134	7.2	0.283 46	16.2	0.637 79	25.2	0.992 12
38/50	0.029 921	7.4	0.291 34	16.4	0.645 67	25.4	1.000 00
39/50	0.030 709	7.6	0.299 21	16.6	0.653 54		
40/50	0.031 496	7.8	0.307 09	16.8	0.661 42		
41/50	0.032 283	8	0.314 96	17	0.669 29		
42/50	0.033 071	8.2	0.322 83	17.2	0.677 16		
43/50	0.033 858	8.4	0.330 71	17.4	0.685 04		
44/50	0.034 646	8.6	0.338 58	17.6	0.692 91		
45/50	0.035 433	8.8	0.346 46	17.8	0.700 79		

*For more complete conversion tables refer to Circular 47, Bureau of Standards, Washington, D. C.

Interconversion Table for Units of Energy

Multiply by

To Convert from	To B.t.u.	To Cal.	To F.t.-lb.	To Ft. Tons	To Kg.-m.	To Hp.-hr.	To Kw.-hr.	To Joules (abs.)	To Lb. G.	To Lb. H ₂ O
B.t.u. (mean).....	1.00	0.252	778.000	0.385001	107.563	0.03929	0.02931	1054.8	0.046876	0.001031
Calories (mean).....	3.968	1.000	3091.36	1.544	426.84	0.001559	0.001163	4185	0.02729	0.004089
Ft.-lb.	0.001285	0.03239	1.000	0.000500	0.1383	0.005050	0.03767	1.355	0.008840	0.001325
Ft. Tons	2.571	0.6478	2000.00	1.000	276.511	0.001010	0.007535	2712.59	0.011768	0.002849
Kg.-m.	0.002343	0.002343	7.23301	0.003617	1.000	0.003653	0.02725	9.806	0.06394	0.009580
Hp.-hr.	0.009297	641.327	1980000	990.004	273747	1.000	0.746000	2685600	0.1750	2.62261
Kw.-hr.	2544.99	859.702	2654200	1327.10	366959	1.34041	1.000	3600000	0.2346	3.51562
Joules (absolute).....	3411.57	0.02389	0.02389	0.003687	0.101937	0.003725	0.02778	1.000	0.06518	0.009766
Lbs. C ₂ H ₅ O.....	14544	3665	1131505	5658	1564396	5.714	4.263	1534703	1.000	14.98
Lbs. H ₂ O.....	970.40	244.537	754971	377.487	104379	0.381270	0.28424	1023966	0.06674	1.000

Note: The small subnumeral following a zero indicates that the zero is to be taken that number of times, thus, 0.01428 is equivalent to 0.0001428. The ton used is 2000 lb. "Lb. C" refers to pounds of carbon oxidized, 100% efficiency equivalent to the corresponding number of heat units. "Lb. H₂O" refers to pounds of water evaporated at 100°C. (212°F.) at 100% efficiency.

Interconversion Table for Units of Volume and Weight

Multiply by

To Convert From	To Cu.in.	To Cu.ft.	To Cu.yd.	To Floz.	To Pt.	To Qt.	To Gal.	To Grain	To Oz.Troy	To Oz.AV.	To Lb.Troy	To Lb. Av.	To C.C. or G.	To L. or Kg.
Cu.in.	1.00000	0.067787	0.02143	0.554112	0.034632	0.017316	0.004329	252.891	0.526857	0.578037	0.03905	0.036127	16.3871	0.016387
Cu.ft.	1728.00	1.00000	0.037037	957.505	59.8442	29.9221	7.48052	436996	910.408	998.848	75.8674	62.4280	283116.5	28.3169
Cu.yd.	46656.0	27.0000	1.00000	25852.6	1615.79	807.896	201.974	1179905	24881.0	26968.9	2048.42	1685.56	764556	764.556
Floz.	1.80469	0.01044	0.03888	1.00000	0.062500	0.031250	0.007813	456.390	0.950813	1.04318	0.079234	0.065199	29.5736	0.029573
Pt.	28.8750	0.016710	0.06189	16.0000	1.00000	0.500000	0.125000	7302.23	15.2130	16.6908	1.26775	1.04318	47.3177	4.73177
Qt.	57.7500	0.033420	0.01238	32.0000	2.00000	1.00000	0.250000	1460.45	30.4260	33.3818	2.53550	2.08635	946.354	94.6354
Gal.	231.000	0.133681	0.04951	128.000	8.00000	4.00000	1.00000	58417.9	121.704	133.527	10.1420	8.34541	3785.42	3.78542
Grain	0.003954	0.002268	0.00475	0.002191	0.01369	0.006850	0.01712	1.00000	0.002083	0.002285	0.01735	0.01428	0.064769	0.064769
Oz. Troy.....	1.83805	0.001098	0.04068	1.05173	0.065732	0.032867	0.008217	480.000	1.00000	1.09714	0.083323	0.068571	31.1035	0.031104
Oz. Av.....	1.72599	0.001001	0.043708	0.958608	0.059913	0.029957	0.007469	437.500	0.91457	1.00000	0.079555	0.062500	28.3495	0.028350
Lb.	22.7766	0.013161	0.044682	12.6208	0.788800	0.394400	0.086600	5760.00	12.0000	13.1607	1.00000	0.822857	37.3242	3.73242
Lb. Av.....	27.6799	0.016018	0.055933	15.3378	0.958611	0.479306	0.119828	7000.00	14.5833	16.0000	1.21528	1.00000	453.593	45.3593
C.C. or G.	0.061024	0.03531	0.01308	0.033814	0.002113	0.001057	0.026642	15.4323	0.032151	0.035274	0.002679	0.002205	1.00000	0.001000
L. or Kg.....	61.0237	0.035315	0.001308	33.8140	2.11337	1.05669	0.264172	15432.3	32.1507	35.2739	2.67923	2.20462	1000.00	1.00000

Note: The small subnumeral following a zero indicates that the zero is to be taken that number of times, thus, 0.01428 is equivalent to 0.0001428. Values Used in Constructing Table: 1 in. = 2.540001 cm.; 1 cu. in. = 16.387083 g. H₂O at 4°C. (39°F.); 1 lb. av. = 453.5926 g; 1 gal. = 8.34541 lb.; 1 lb. av. = 27.679986 cu. in. H₂O at 4°C.; 1 lb. av. = 7000 grains; 1 gal = 58417.87 grains; 231 cu. in. = 1 gal. = 3785.4162 g.

Comparative Table of Wire and Sheet Gages

Dimensions of Sizes in Decimal Parts of an Inch

No. of Wire Gage	American or B. & S.	Birmingham or Stubbs' Iron Wire	Steel Wire Gage	W. & M. Steel Music Wire	New Am. S. & W. Co.'s Music Wire Gage	Imperial Wire Gage	Stubbs' Steel Wire	U. S. Standard Gage for Sheet and Plate Iron and Steel	No. of Wire Gage
00000000	.....	.....	.....	0.0083	.....	.....	.....	.....	00000000
0000000	.....	.....	0.490	0.0087	.....	.....	.....	.....	0000000
000000	.....	.....	0.4615	0.0095	0.004	0.464	.....	0.46875	000000
00000	.....	.....	0.4305	0.010	0.005	0.432	.....	0.4375	00000
0000	0.460	0.454	0.3938	0.011	0.006	0.400	.....	0.40625	0000
000	0.40964	0.425	0.3625	0.012	0.007	0.372	.....	0.375	000
00	0.3648	0.380	0.3310	0.0133	0.008	0.348	.....	0.34375	00
0	0.32486	0.340	0.3085	0.0144	0.009	0.324	.....	0.3125	0
1	0.2893	0.300	0.2830	0.0156	0.010	0.300	0.227	0.28125	1
2	0.25763	0.284	0.2625	0.0166	0.011	0.276	0.219	0.265625	2
3	0.22942	0.259	0.2437	0.0178	0.012	0.252	0.212	0.250	3
4	0.20431	0.238	0.2253	0.0188	0.013	0.232	0.207	0.234375	4
5	0.18194	0.220	0.2070	0.0202	0.014	0.212	0.204	0.21875	5
6	0.16202	0.203	0.1920	0.0215	0.016	0.192	0.201	0.203125	6
7	0.14428	0.180	0.1770	0.023	0.018	0.176	0.199	0.1875	7
8	0.12849	0.165	0.1620	0.0243	0.020	0.160	0.197	0.171875	8
9	0.11443	0.148	0.1483	0.0256	0.022	0.144	0.194	0.15625	9
10	0.10189	0.134	0.1350	0.027	0.024	0.128	0.191	0.140625	10
11	0.090742	0.120	0.1205	0.0284	0.026	0.116	0.188	0.125	11
12	0.080808	0.109	0.1055	0.0296	0.029	0.104	0.185	0.109375	12
13	0.071961	0.095	0.0915	0.0314	0.031	0.092	0.182	0.09375	13
14	0.064804	0.083	0.0800	0.0326	0.033	0.080	0.180	0.078125	14
15	0.057068	0.072	0.0720	0.0345	0.035	0.072	0.178	0.0703125	15
16	0.05082	0.065	0.0625	0.036	0.037	0.064	0.175	0.0625	16
17	0.045257	0.058	0.0540	0.0377	0.039	0.056	0.172	0.05625	17
18	0.040303	0.049	0.0475	0.0395	0.041	0.048	0.168	0.050	18
19	0.03589	0.042	0.0410	0.0414	0.043	0.040	0.164	0.04375	19
20	0.031961	0.035	0.0348	0.0434	0.045	0.036	0.161	0.0375	20
21	0.028462	0.032	0.03175	0.046	0.047	0.032	0.157	0.034375	21
22	0.025347	0.028	0.0286	0.0483	0.049	0.028	0.155	0.03125	22
23	0.022571	0.025	0.0258	0.051	0.051	0.024	0.153	0.028125	23
24	0.0201	0.022	0.0230	0.055	0.055	0.022	0.151	0.025	24
25	0.0179	0.020	0.0204	0.0586	0.059	0.020	0.148	0.021875	25
26	0.01594	0.018	0.0181	0.0626	0.063	0.018	0.146	0.01875	26
27	0.014195	0.016	0.0173	0.0658	0.067	0.0164	0.143	0.0171875	27
28	0.012641	0.014	0.0162	0.072	0.071	0.0149	0.139	0.015625	28
29	0.011257	0.013	0.0150	0.076	0.075	0.0136	0.134	0.0140625	29
30	0.010025	0.012	0.0140	0.080	0.080	0.0124	0.127	0.0125	30
31	0.008928	0.010	0.0132	.....	0.085	0.0116	0.120	0.0109375	31
32	0.00795	0.009	0.0128	.....	0.090	0.0108	0.115	0.01015625	32
33	0.00708	0.008	0.0118	.....	0.095	0.0100	0.112	0.009375	33
34	0.006304	0.007	0.0104	.....	.....	0.0092	0.110	0.00859375	34
35	0.005614	0.005	0.0095	.....	.....	0.0084	0.108	0.0078125	35
36	0.005	0.004	0.0090	.....	.....	0.0076	0.106	0.00703125	36
37	0.004453	.....	.....	.....	.....	0.0068	0.103	0.00640625	37
38	0.003965	.....	.....	.....	.....	0.0060	0.101	0.00625	38
39	0.003531	.....	.....	.....	.....	0.0052	0.099	.....	39
40	0.003144	.....	.....	.....	.....	0.0048	0.097	.....	40

Weights of Steel Bars

Carbon Steels—Approximate weights of carbon steel bars in rounds, squares, hexagons, octagons, and flats are given in the following tables. The weights given have been calculated from the unit, 1 cu. in. equals 0.2833 lb. or its equivalent, 1 cu. ft. equals 489.54 lb. A convenient unit much used in practice is 1 cu. in. equals 0.3 lb. This gives weights about 6% heavier than those in the tables, but since bar steel is usually furnished slightly full to size, weights calculated on this basis yield fairly close working results for all except very large sizes.

High Speed Steels—On account of the large proportion of special elements present, high speed steels are heavier than carbon steels. While this increased weight is not constant, a fairly close estimation of the weight of high speed steels may be obtained by adding 10% to the figures for carbon steels as given in the tables. In other words, multiply the figures in the tables by 1.1 to obtain the weight of high speed steel.

Useful Methods for Calculating Weights—There are several methods which may often be used to advantage in determining weights of odd-sized bars not included in the subsequent tables.

(1) To find the weight per ft. of any size round, square or octagon, square the diameter (or stated dimension) and multiply by the weight per ft. of 1 in. round, square or octagon, respectively.

(2) The weight per ft. of octagon steel may be found by multiplying the weight per ft. of a round bar of the same size by 1.0547.

(3) The weight per ft. of hexagon steel may be found by multiplying the weight per ft. of a round bar of the same size by 1.1026.

(4) To find the weight per ft. of any flat, multiply the product of the width and thickness by the weight per ft. of 1 in. sq.

Weights and Areas of Carbon Steel Bars
Weight per Lineal Ft. and per In. in Lb.

Size Round or Square, In.	ROUND BARS		SQUARE BARS		OCTAGON BARS		HEXAGON BARS	
	Area, Sq. in.	Weight, Per Ft.	Area, Sq. in.	Weight, Per Ft.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.	Weight, Per In.
1	0.0031	0.00087	0.0039	0.001083	0.011	0.000917	0.0046	0.00383
1/8	0.0123	0.0035	0.0156	0.00441	0.044	0.00367	0.046	0.00383
1/4	0.0276	0.00783	0.0352	0.00991	0.099	0.00825	0.10	0.00383
3/8	0.0491	0.0139	0.0625	0.01766	0.212	0.0147	0.18	0.015
1/2	0.0767	0.0217	0.0977	0.0278	0.376	0.0233	0.29	0.0242
5/8	0.1105	0.0312	0.1406	0.0398	0.478	0.033	0.41	0.0342
3/4	0.1503	0.0425	0.1914	0.0543	0.651	0.045	0.56	0.0466
7/8	0.1964	0.0555	0.25	0.0708	0.850	0.0588	0.74	0.0616
1	0.2485	0.0704	0.3164	0.0897	1.076	0.0744	0.93	0.0775
1 1/8	0.3068	0.0867	0.3906	0.1106	1.328	0.09183	1.15	0.0958
1 1/4	0.3712	0.105	0.4727	0.134	1.608	0.1104	1.40	0.1166
1 1/2	0.4418	0.125	0.5625	0.1594	1.913	0.1323	1.66	0.1383
1 3/4	0.5185	0.1469	0.6602	0.187	2.245	0.1552	1.94	0.1617
2	0.6013	0.1703	0.7656	0.217	2.603	0.1801	2.25	0.1875
2 1/8	0.6902	0.2044	0.8789	0.249	2.989	0.2067	2.59	0.2158
2 1/4	0.7854	0.2347	1.000	0.283	3.400	0.2351	2.94	0.245
2 1/2	0.8866	0.2611	1.1289	0.320	3.838	0.2655	3.32	0.2766
2 3/4	0.9940	0.2815	1.2656	0.3585	4.303	0.2976	3.73	0.3108
3	1.1075	0.3138	1.41	0.3996	4.795	0.3316	4.15	0.3458
3 1/8	1.2272	0.3477	1.56	0.4427	5.312	0.3674	4.60	0.3833
3 1/4	1.3530	0.3833	1.72	0.486	5.857	0.405	5.06	0.4216
3 1/2	1.4849	0.4207	1.89	0.5357	6.428	0.4445	5.54	0.4616
3 3/4	1.6230	0.4598	2.07	0.5855	7.026	0.486	6.06	0.505
4	1.7671	0.5007	2.25	0.6375	7.650	0.529	6.63	0.5525
4 1/8	1.9175	0.5433	2.44	0.6917	8.301	0.5741	7.17	0.5975
4 1/4	2.0739	0.5875	2.64	0.748	8.978	0.621	7.78	0.6483
4 1/2	2.2365	0.6336	2.85	0.8068	9.682	0.6696	8.37	0.6975
4 3/4	2.4053	0.6815	3.06	0.8675	10.41	0.72	9.02	0.7514
5	2.5802	0.731	3.29	0.9308	11.17	0.7725	9.67	0.8058
5 1/8	2.7612	0.782	3.52	0.9958	11.95	0.8265	10.36	0.8633
5 1/4	2.9483	0.835	3.75	1.063	12.76	0.889	11.05	0.92
5 1/2	3.1416	0.89	4.00	1.133	13.60	0.9408	11.78	0.9817
5 3/4	3.3410	0.947	4.25	1.205	14.46	1.0	12.51	1.042
6	3.5466	1.005	4.52	1.279	15.35	1.062	13.30	1.108
6 1/8	3.7583	1.065	4.79	1.355	16.27	1.125	14.08	1.173
6 1/4	3.9761	1.128	5.06	1.435	17.22	1.1908	14.91	1.243
6 1/2	4.200	1.19	5.35	1.515	18.19	1.259	15.74	1.312
6 3/4	4.4301	1.255	5.64	1.598	19.18	1.3268	16.62	1.383
7	4.6664	1.32	5.94	1.683	20.20	1.3975	17.50	1.458
7 1/8	4.9087	1.39	6.25	1.771	21.25	1.47	18.41	1.534
7 1/4	5.1572	1.46	6.57	1.861	22.33	1.5441	19.35	1.612
7 1/2	5.4119	1.533	6.89	1.952	23.43	1.62	20.30	1.691
7 3/4	5.6727	1.607	7.22	2.046	24.56	1.698	21.28	1.773

(Continued)

Weights and Areas of Carbon Steel Bars
Weight per Lineal Ft. and per In. in Lb.

Size, Round or Square, In.	ROUND BARS			SQUARE BARS			OCTAGON BARS			HEXAGON BARS		
	Area, Sq. In.	Weight, Per In.	Weight, Per Ft.	Area, Sq. In.	Weight, Per In.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.
$\frac{3}{4}$	5.9396	1.683	20.20	7.56	2.083	25.00	20.75	1.729	22.28	1.857	22.28	1.857
$\frac{1}{2}$	6.2136	1.76	21.12	7.91	2.241	26.90	22.32	1.861	23.30	1.942	23.30	1.942
$\frac{1}{4}$	6.4918	1.84	22.07	8.27	2.341	28.10	23.33	1.943	24.34	2.03	24.34	2.03
$\frac{3}{8}$	6.7771	1.916	23.04	8.63	2.445	29.34	24.35	2.029	25.40	2.117	25.40	2.117
3	7.0686	2.00	24.03	9.00	2.55	30.60	25.40	2.117	26.51	2.209	26.51	2.209
$\frac{1}{2}$	7.3662	2.087	25.04	9.3769	2.658	31.89	26.47	2.205	27.69	2.304	27.69	2.304
$\frac{1}{4}$	7.6699	2.173	26.08	9.7656	2.768	33.20	27.56	2.296	28.77	2.397	28.77	2.397
$\frac{1}{2}$	7.9798	2.275	27.13	10.16	2.88	34.55	28.68	2.39	29.90	2.491	29.90	2.491
$\frac{3}{8}$	8.2958	2.35	28.20	10.56	2.993	35.92	29.81	2.484	31.10	2.591	31.10	2.591
$\frac{1}{2}$	8.6179	2.441	29.30	10.97	3.11	37.31	30.97	2.58	32.29	2.69	32.29	2.69
$\frac{1}{4}$	8.9462	2.533	30.42	11.39	3.23	38.73	32.15	2.679	33.45	2.812	33.45	2.812
$\frac{3}{8}$	9.2806	2.63	31.56	11.82	3.348	40.18	33.35	2.78	34.75	2.895	34.75	2.895
$\frac{1}{2}$	9.6211	2.726	32.71	12.95	3.47	41.65	34.57	2.88	36.08	3.00	36.08	3.00
$\frac{3}{4}$	9.9678	2.825	33.90	13.69	3.595	43.14	35.81	2.983	37.34	3.11	37.34	3.11
4	10.321	2.92	35.09	14.54	3.723	44.68	37.08	3.09	38.70	3.225	38.70	3.225
$\frac{1}{2}$	10.680	3.026	36.31	15.015	3.853	46.24	38.38	3.20	40.00	3.333	40.00	3.333
$\frac{3}{4}$	11.045	3.13	37.56	15.51	3.993	47.82	39.69	3.31	41.43	3.452	41.43	3.452
$\frac{1}{2}$	11.416	3.234	38.81	16.00	4.118	49.42	41.02	3.42	42.75	3.562	42.75	3.562
$\frac{3}{8}$	11.793	3.342	40.10	16.51	4.254	51.05	42.39	3.53	44.20	3.683	44.20	3.683
$\frac{1}{2}$	12.177	3.45	41.40	17.02	4.392	52.71	43.75	3.646	45.65	3.804	45.65	3.804
$\frac{3}{4}$	12.566	3.56	42.73	17.51	4.533	54.40	45.15	3.762	47.13	3.927	47.13	3.927
5	12.962	3.672	44.07	18.00	4.675	56.11	46.57	3.88				
$\frac{1}{2}$	13.364	3.783	45.44	18.51	4.819	57.85	48.02	4.00	53.21	4.434	53.21	4.434
$\frac{3}{4}$	13.772	3.9	46.83	19.02	4.968	59.62	49.48	4.123				
6	14.186	4.02	48.24	19.51	5.117	61.41	50.97	4.247				
$\frac{1}{2}$	14.607	4.138	49.66	20.00	5.27	63.23	52.48	4.373				
$\frac{3}{4}$	15.033	4.259	51.11	20.51	5.42	65.08	54.02	4.5				
$\frac{1}{2}$	15.466	4.381	52.58	21.00	5.58	66.95	55.57	4.63				
$\frac{3}{8}$	15.904	4.505	54.07	21.51	5.737	68.85	57.15	4.762				
$\frac{1}{2}$	16.349	4.632	55.59	22.00	5.898	70.78	58.75	4.895				
$\frac{3}{4}$	16.800	4.76	57.12	22.51	6.06	72.73	60.37	5.03				
7	17.257	4.89	58.67	23.00	6.225	74.70	62.00	5.166				
$\frac{1}{2}$	17.721	5.02	60.25	23.51	6.392	76.71	63.67	5.305				
$\frac{3}{4}$	18.190	5.153	61.84	24.00	6.562	78.74	65.35	5.446				
8	18.665	5.288	63.46	24.51	6.734	80.81	67.07	5.59				
$\frac{1}{2}$	19.147	5.416	65.10	25.00	6.907	82.89	68.80	5.733				
$\frac{3}{4}$	19.635	5.563	66.76	25.51	7.083	85.00	70.55	5.879				
9	20.129	5.703	68.44	26.00	7.263	87.14	72.33	6.028				
$\frac{1}{2}$	20.629	5.845	70.14	26.51	7.444	89.30	74.12	6.176				
$\frac{3}{4}$	21.135	5.988	71.86	27.00	7.624	91.49	75.94	6.328				
10	21.648	6.133	73.60	27.51	7.81	93.72	77.79	6.483				
$\frac{1}{2}$	22.166	6.28	75.37	28.00	7.997	95.95	79.65	6.637				
$\frac{3}{4}$	22.691	6.43	77.15	28.51	8.185	98.23	81.53	6.794				
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Weights and Areas of Carbon Steel Bars
Weight per Lineal Ft. and per In. in Lb.

Size, Round or Square, In.	ROUND BARS			SQUARE BARS			OCTAGON BARS			HEXAGON BARS		
	Area, Sq. In.	Weight, Per In.	Weight, Per Ft.	Area, Sq. In.	Weight, Per In.	Weight, Per Ft.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.	Weight, Per Ft.	Weight, Per In.	Weight, Per Ft.
$\frac{1}{16}$	23.221	6.579	76.95	29.57	8.375	100.5	83.42	6.951	89.09	7.424		
$\frac{1}{8}$	23.758	6.73	80.77	30.25	8.566	102.8	85.32	7.11				
$\frac{3}{16}$	24.301	6.885	82.62	30.95	8.77	105.2	87.31	7.276				
$\frac{1}{4}$	24.850	7.04	84.49	31.64	8.97	107.6	89.31	7.442				
$\frac{5}{16}$	25.406	7.198	86.38	32.35	9.17	110.0	91.30	7.608				
$\frac{3}{8}$	25.967	7.358	88.29	33.06	9.37	112.4	93.29	7.774				
$\frac{7}{16}$	26.535	7.518	90.22	33.79	9.58	114.9	95.37	7.947				
$\frac{1}{2}$	27.109	7.68	92.17	34.52	9.783	117.4	97.44	8.12				
$\frac{5}{8}$	27.688	7.845	94.14	35.26	9.991	119.9	99.52	8.293				
$\frac{3}{4}$	28.274	8.01	96.14	36.00	10.2	122.4	101.6	8.468				
$\frac{7}{8}$	28.850	8.178	98.14	36.76	10.416	125.0	103.8	8.65				
1	29.465	8.35	100.2	37.52	10.633	127.6	105.9	8.825				
$1\frac{1}{8}$	30.06	8.51	102.2	38.29	10.85	130.2	108.1	9.00				
$1\frac{1}{4}$	30.680	8.69	104.3	39.06	11.07	132.8	110.2	9.183				
$1\frac{3}{8}$	31.29	8.875	106.4	39.85	11.3	135.5	112.47	9.372				
$1\frac{1}{2}$	31.92	9.04	108.5	40.64	11.51	138.2	114.7	9.558				
$1\frac{3}{4}$	32.55	9.225	110.7	41.45	11.74	140.9	116.9	9.742				
2	33.18	9.4	112.8	42.25	11.97	143.6	119.2	9.933				
$2\frac{1}{8}$	33.80	9.575	114.9	43.07	12.2	146.5	121.6	10.133				
$2\frac{1}{4}$	34.49	9.766	117.2	43.89	12.43	149.2	123.8	10.316				
$2\frac{3}{8}$	35.12	9.95	119.4	44.73	12.675	152.1	126.2	10.516				
$2\frac{1}{2}$	35.78	10.14	121.7	45.56	12.99	154.9	128.6	10.716				
$2\frac{3}{4}$	36.44	10.325	123.9	46.42	13.15	157.8	131.0	10.916				
3	37.13	10.51	126.2	47.27	13.4	160.8	133.5	11.125				
$3\frac{1}{8}$	37.79	10.708	128.5	48.14	13.633	163.6	135.8	11.316				
$3\frac{1}{4}$	38.48	10.908	130.9	49.00	13.883	166.6	138.3	11.525				
$3\frac{3}{8}$	39.18	11.1	133.2	49.89	14.13	169.6	140.8	11.733				
$3\frac{1}{2}$	39.88	11.3	135.6	50.77	14.383	172.6	143.3	11.941				
$3\frac{3}{4}$	40.59	11.5	137.9	51.67	14.633	175.6	145.7	12.141				
4	41.28	11.7	140.4	52.56	14.891	178.7	148.3	12.36				
$4\frac{1}{8}$	42.00	11.9	142.8	53.48	15.15	181.8	150.8	12.57				
$4\frac{1}{4}$	42.73	12.108	145.3	54.39	15.408	184.9	153.5	12.79				
$4\frac{3}{8}$	43.45	12.308	147.7	55.32	15.675	188.1	156.1	13.00				
$4\frac{1}{2}$	44.17	12.517	150.2	56.25	15.94	191.3	158.8	13.23				
$4\frac{3}{4}$	44.88	12.75	152.5	57.14	16.215	194.7	161.2	13.48				
5	45.68	13.008	155.2	58.14	16.475	197.7	163.5	13.73				
$5\frac{1}{8}$	46.47	13.258	158.0	59.06	16.745	200.2	165.8	13.98				
$5\frac{1}{4}$	47.19	13.5	160.3	60.06	17.016	202.6	168.5	14.23				
$5\frac{3}{8}$	47.93	13.8	162.6	61.06	17.286	205.1	170.8	14.48				
$5\frac{1}{2}$	48.73	14.25	171.0	62.33	18.133	217.6	180.6	15.05				
6	50.26	15.2	181.4	64.00	18.333	227.8	188.3	15.83				
$6\frac{1}{8}$	51.01	15.45	184.0	64.81	18.583	232.4	193.3	16.38				
$6\frac{1}{4}$	51.76	15.708	186.6	65.64	18.833	237.0	198.3	16.93				
$6\frac{3}{8}$	52.51	15.958	189.2	66.47	19.083	241.6	203.3	17.48				
$6\frac{1}{2}$	53.26	16.208	191.8	67.31	19.333	246.2	208.3	18.03				
$6\frac{3}{4}$	54.01	16.458	194.4	68.14	19.583	250.8	213.3	18.58				
7	54.76	16.708	197.0	68.98	19.833	255.4	218.3	19.13				
$7\frac{1}{8}$	55.51	16.958	199.6	69.81	20.083	260.0	223.3	19.68				
$7\frac{1}{4}$	56.26	17.208	202.2	70.64	20.333	264.6	228.3	20.23				
$7\frac{3}{8}$	57.01	17.458	204.8	71.47	20.583	269.2	233.3	20.78				
$7\frac{1}{2}$	57.76	17.708	207.4	72.31	20.833	273.8	238.3	21.33				
$7\frac{3}{4}$	58.51	17.958	210.0	73.14	21.083	278.4	243.3	21.88				
8	59.26	18.208	212.6	73.98	21.333	283.0	248.3	22.43				
$8\frac{1}{8}$	60.01	18.458	215.2	74.81	21.583	287.6	253.3	22.98				
$8\frac{1}{4}$	60.76	18.708	217.8	75.64	21.833	292.2	258.3	23.53				
$8\frac{3}{8}$	61.51	18.958	220.4	76.47	22.083	296.8	263.3	24.08				
$8\frac{1}{2}$	62.26	19.208	223.0	77.31	22.333	301.4	268.3	24.63				
$8\frac{3}{4}$	63.01	19.458	225.6	78.14	22.583	306.0	273.3	25.18				
9	63.76	19.708	228.2	78.98	22.833	310.6	278.3	25.73				
$9\frac{1}{8}$	64.51	19.958	230.8	79.81	23.083	315.2	283.3	26.28				
$9\frac{1}{4}$	65.26	20.208	233.4	80.64	23.333	319.8	288.3	26.83				
$9\frac{3}{8}$	66.01	20.458	236.0	81.47	23.583	324.4	293.3	27.38				
$9\frac{1}{2}$	66.76	20.708	238.6	82.31	23.833	329.0	298.3	27.93				
$9\frac{3}{4}$	67.51	20.958	241.2	83.14	24.083	333.6	303.3	28.48				
10	68.26	21.208	243.8	83.98	24.333	338.2	308.3	29.03				
$10\frac{1}{8}$	69.01	21.458	246.4	84.81	24.583	342.8	313.3	29.58				
$10\frac{1}{4}$	69.76	21.708	249.0	85.64	24.833	347.4	318.3	30.13				
$10\frac{3}{8}$	70.51	21.958	251.6	86.47	25.083	352.0	323.3	30.68				
$10\frac{1}{2}$	71.26	22.208	254.2	87.31	25.333	356.6	328.3	31.23				
$10\frac{3}{4}$	72.01	22.458	256.8	88.14	25.583	361.2	333.3	31.78				
11	72.76	22.708	259.4	88.98	25.833	365.8	338.3	32.33				
$11\frac{1}{8}$	73.51	22.958	262.0	89.81	26.083	370.4	343.3	32.88				
$11\frac{1}{4}$	74.26	23.208	264.6	90.64	26.333	375.0	348.3	33.43				
$11\frac{3}{8}$	75.01	23.458	267.2	91.47	26.583	379.6	353.3	33.98				
$11\frac{1}{2}$	75.76	23.708	269.8	92.31	26.833	384.2	358.3	34.53				
$11\frac{3}{4}$	76.51	23.958	272.4	93.14	27.083	388.8	363.3	35.08				
12	77.26	24.208	275.0	93.98	27.333	393.4	368.3	35.63				
$12\frac{1}{8}$	78.01	24.458	277.6	94.81	27.583	398.0	373.3	36.18				
$12\frac{1}{4}$	78.76	24.708	280.2	95.64	27.833	402.6	378.3	36.73				
$12\frac{3}{8}$	79.51	24.958	282.8	96.47	28.083	407.2	383.3	37.28				
$12\frac{1}{2}$	80.26	25.208	285.4	97.31	28.333	411.8	388.3	37.83				
$12\frac{3}{4}$	81.01	25.458	288.0	98.14	28.583	416.4	393.3	38.38				
13	81.76	25.708	290.6	98.98	28.833	421.0	398.3	38.93				
$13\frac{1}{8}$	82.51	25.958	293.2	99.81	29.083	425.6	403.3	39.48				
$13\frac{1}{4}$	83.26	26.208	295.8	100.64	29.333	430.2	408.3	40.03				
$13\frac{3}{8}$	84.01	26.458	298.4	101.47	29.583	434.8	413.3	40.58				
$13\frac{1}{2}$	84.76	26.708	301.0	102.31	29.833	439.4	418.3	41.13				
$13\frac{3}{4}$	85.51	26.958	303.6	103.14	30.083	444.0	423.3	41.68				
14	86.26	27.208	306.2	103.98	30.333	448.6	428.3	42.23				
$14\frac{1}{8}$	87.01	27.458	308.8	104.81	30.583	453.2	433.3	42.78				
$14\frac{1}{4}$	87.76	27.708	311.4	105.64	30.833	457.8	438.3	43.33				
$14\frac{3}{8}$	88.51	27.958	314.0	106.47	31.083	462.4	443.3	43.88				
$14\frac{1}{2}$	89.26	28.208	316.6	107.31	31.333	467.0	448.3	44.43				
$14\frac{3}{4}$	90.01	28.458	319.2	108.14	31.583	471.6	453.3	44.98				
15	90.76	28.708	321.8	108.98	31.833	476.2	458.3	45.53				
$15\frac{1}{8}$	91.51	28.958	324.4	109.81	32.083	480.8	463.3	46.08				
$15\frac{1}{4}$	92.26	29.208	327.0	110.64	32.333	485.4	468.3	46.63				
$15\frac{3}{8}$	93.01	29.458	329.6	111.47	32.583	490.0	473.3	47.18				
$15\frac{1}{2}$	93.76	29.708	332.2	112.31	32.833	494.6	478.3	47.73				
$15\frac{3}{4}$	94.51	29.958	334.8	113.14	33.083	499.2	483.3	48.28				
16	95.26</											

Flat Rolled Carbon Steel

Weight Per Lineal Ft. in Lb.
Width in In.

Thick- ness, In.	½	¾	1	1¼	1½	1¾	2	2¼	2½	2¾	3	3½	4
⅛	0.1060	0.1381	0.1594	0.1859	0.212	0.2391	0.2656	0.292	0.319	0.346	0.372	0.425	0.478
1/16	0.2125	0.2656	0.3188	0.3720	0.4250	0.4782	0.5312	0.585	0.638	0.692	0.744	0.850	0.96
3/16	0.319	0.399	0.478	0.558	0.638	0.717	0.797	0.875	0.957	1.04	1.15	1.28	1.44
¼	0.425	0.531	0.638	0.743	0.850	0.957	1.06	1.17	1.28	1.38	1.49	1.70	1.92
5/16	0.531	0.664	0.797	0.929	1.06	1.20	1.33	1.46	1.59	1.73	1.86	2.12	2.39
3/8	0.638	0.797	0.957	1.116	1.28	1.43	1.59	1.76	1.92	2.08	2.23	2.55	2.87
7/16	0.744	0.929	1.116	1.302	1.49	1.68	1.86	2.05	2.23	2.42	2.60	2.98	3.35
½	0.850	1.06	1.275	1.487	1.70	1.92	2.12	2.34	2.55	2.72	2.98	3.40	3.83
5/8	0.957	1.20	1.434	1.674	1.92	2.15	2.39	2.63	2.87	3.11	3.35	3.83	4.30
¾	1.06	1.33	1.594	1.859	2.12	2.39	2.65	2.92	3.19	3.46	3.72	4.26	4.78
7/8	1.17	1.46	1.753	2.045	2.34	2.63	2.92	3.22	3.51	3.80	4.09	4.67	5.26
1	1.28	1.60	1.913	2.232	2.55	2.87	3.19	3.51	3.83	4.15	4.47	5.10	5.75
1 1/16	1.38	1.73	2.072	2.417	2.76	3.11	3.45	3.80	4.14	4.49	4.84	5.53	6.21
1 1/8	1.49	1.86	2.232	2.604	2.98	3.35	3.72	4.09	4.47	4.84	5.20	5.95	6.69
1 1/4	1.60	1.99	2.391	2.789	3.19	3.59	3.99	4.39	4.78	5.18	5.58	6.38	7.18
1 1/2	1.70	2.13	2.55	2.98	3.40	3.83	4.25	4.68	5.10	5.53	5.95	6.80	7.65
1 3/8	1.81	2.26	2.710	3.161	3.61	4.064	4.52	4.97	5.42	5.87	6.32	7.22	8.13
1 5/8	1.91	2.39	2.868	3.347	3.83	4.304	4.78	5.26	5.74	6.22	6.70	7.65	8.61
1 7/8	2.02	2.52	3.03	3.553	4.04	4.54	5.05	5.56	6.06	6.56	7.07	8.08	9.09
2	2.12	2.66	3.19	3.72	4.25	4.79	5.31	5.85	6.38	6.91	7.44	8.50	9.57
2 1/16	2.23	2.79	3.35	3.91	4.46	5.02	5.58	6.14	6.69	7.25	7.81	8.93	10.04
2 1/8	2.34	2.92	3.51	4.09	4.67	5.26	5.84	6.43	7.02	7.60	8.18	9.35	10.52
2 1/4	2.45	3.06	3.67	4.28	4.89	5.50	6.11	6.72	7.34	7.94	8.56	9.78	11.00
2 1/2	2.55	3.19	3.83	4.47	5.10	5.74	6.38	7.02	7.65	8.29	8.93	10.20	11.48
2 3/8	2.66	3.32	3.99	4.65	5.32	5.98	6.64	7.31	7.97	8.74	9.30	10.63	11.95
2 1/2	2.76	3.45	4.15	4.84	5.52	6.22	6.90	7.60	8.29	8.98	9.67	11.05	12.43
2 7/8	2.87	3.59	4.31	5.02	5.74	6.46	7.17	7.89	8.61	9.30	10.04	11.47	12.91
3	2.98	3.72	4.47	5.21	5.95	6.70	7.44	8.19	8.93	9.67	10.42	11.90	13.40
3 1/16	3.08	3.85	4.62	5.466	6.16	6.93	7.70	8.48	9.24	10.02	10.79	12.33	13.86
3 1/8	3.19	3.99	4.79	5.58	6.38	7.17	7.97	8.77	9.57	10.36	11.15	12.75	14.34
3 1/4	3.30	4.12	4.94	5.77	6.59	7.42	8.24	9.06	9.88	10.71	11.53	13.18	14.83
3 1/2	3.40	4.25	5.10	5.95	6.80	7.65	8.50	9.35	10.20	11.05	11.90	13.60	15.30

Flat Rolled Carbon Steel

Weight Per Lineal Ft. in Lb.
Width in In.

Thick- ness, In.	2½	2¾	3	3¼	3½	3¾	4	4¼	4½	4¾	5	5¼	5½
⅛	0.531	0.584	0.638	0.691	0.744	0.80	0.85	0.90	0.96	1.01	1.06	1.116	1.169
1/16	1.06	1.17	1.28	1.38	1.49	1.59	1.70	1.81	1.91	2.02	2.13	2.232	2.338
3/16	1.59	1.75	1.91	2.07	2.23	2.39	2.55	2.71	2.87	3.03	3.19	3.35	3.51
¼	2.12	2.34	2.55	2.76	2.98	3.19	3.40	3.61	3.83	4.04	4.25	4.46	4.67
5/16	2.65	2.92	3.19	3.45	3.72	3.99	4.25	4.52	4.78	5.05	5.31	5.58	5.84
3/8	3.19	3.51	3.83	4.15	4.47	4.78	5.10	5.42	5.74	6.06	6.38	6.69	7.02
7/16	3.72	4.09	4.46	4.83	5.20	5.58	5.95	6.32	6.70	7.07	7.44	7.81	8.18
½	4.25	4.67	5.10	5.53	5.95	6.38	6.80	7.22	7.65	8.08	8.50	8.93	9.35
5/8	4.78	5.26	5.74	6.22	6.70	7.17	7.65	8.13	8.61	9.09	9.57	10.04	10.52
¾	5.31	5.84	6.38	6.91	7.44	7.97	8.50	9.03	9.57	10.10	10.63	11.16	11.69
7/8	5.84	6.43	7.02	7.60	8.18	8.76	9.35	9.93	10.52	11.11	11.69	12.27	12.85
1	6.38	7.02	7.65	8.29	8.93	9.57	10.20	10.84	11.48	12.12	12.75	13.39	14.03
1 1/16	6.90	7.60	8.29	8.98	9.67	10.36	11.05	11.74	12.43	13.12	13.81	14.50	15.19

(Continued)

Flat Rolled Carbon Steel
Weight Per Lineal Ft. in Lb.
Width in In.

Thick- ness, In.	2½	2¾	3	3¼	3½	3¾	4	4¼	4½	4¾	5	5¼	5½
⅜	7.44	8.18	8.93	9.67	10.41	11.16	11.90	12.65	13.39	14.13	14.87	15.62	16.36
7/16	7.97	8.77	9.57	10.36	11.16	11.95	12.75	13.55	14.34	15.14	15.94	16.74	17.53
1/2	8.50	9.35	10.20	11.05	11.90	12.75	13.60	14.45	15.30	16.15	17.00	17.85	18.70
11/16	9.03	9.93	10.84	11.74	12.65	13.55	14.45	15.35	16.26	17.16	18.06	18.96	19.87
13/16	9.57	10.52	11.48	12.43	13.39	14.34	15.30	16.26	17.22	18.17	19.13	20.08	21.04
1½	10.10	11.11	12.12	13.12	14.13	15.14	16.15	17.16	18.17	19.18	20.19	21.20	22.21
1¾	10.63	11.69	12.75	13.81	14.87	15.94	17.00	18.06	19.13	20.19	21.25	22.32	23.38
1⅞	11.16	12.27	13.39	14.50	15.62	16.74	17.85	18.96	20.08	21.20	22.32	23.43	24.54
2	11.69	12.85	14.03	15.20	16.36	17.53	18.70	19.87	21.04	22.21	23.38	24.54	25.71
2½	12.22	13.44	14.66	15.88	17.10	18.33	19.55	20.77	21.99	23.22	24.44	25.66	26.88
3	12.75	14.03	15.30	16.58	17.85	19.13	20.40	21.68	22.95	24.23	25.50	26.78	28.05
3½	13.28	14.61	15.94	17.27	18.60	19.92	21.25	22.58	23.91	25.24	26.57	27.89	29.22
4	13.81	15.19	16.58	17.96	19.34	20.72	22.10	23.48	24.87	26.25	27.63	29.01	30.39
4½	14.34	15.78	17.22	18.65	20.08	21.51	22.95	24.38	25.82	27.26	28.69	30.12	31.55
5	14.88	16.37	17.85	19.34	20.83	22.32	23.80	25.29	26.78	28.27	29.75	31.24	32.73
5½	15.40	16.95	18.49	20.03	21.57	23.11	24.65	26.19	27.73	29.27	30.81	32.35	33.89
6	15.94	17.53	19.13	20.72	22.31	23.91	25.50	27.10	28.69	30.28	31.87	33.47	35.06
6½	16.47	18.12	19.77	21.41	23.06	24.70	26.35	28.00	29.64	31.29	32.94	34.59	36.23
7	17.00	18.70	20.40	22.10	23.80	25.50	27.20	28.90	30.60	32.30	34.00	35.70	37.40

Flat Rolled Carbon Steel
Weight Per Lineal Ft. in Lb.
Width in In.

Thick- ness, In.	5½	6	6¼	6½	6¾	7	7¼	7½	7¾	8	8¼	8½	8¾
⅜	1.222	1.275	1.328	1.381	1.434	1.487	1.540	1.594	1.647	1.70	1.753	1.806	1.859
7/16	2.444	2.550	2.656	2.762	2.869	2.975	3.081	3.188	3.294	3.40	3.506	3.612	3.720
1/2	3.67	3.83	3.99	4.14	4.30	4.46	4.62	4.78	4.94	5.10	5.26	5.42	5.58
11/16	4.89	5.10	5.31	5.53	5.74	5.95	6.16	6.36	6.58	6.80	7.01	7.22	7.43
13/16	6.11	6.38	6.64	6.90	7.17	7.44	7.70	7.97	8.23	8.50	8.76	9.03	9.29
15/16	7.34	7.65	7.97	8.29	8.61	8.93	9.25	9.57	9.88	10.20	10.52	10.84	11.16
1¾	8.56	8.93	9.29	9.67	10.04	10.41	10.78	11.16	11.53	11.90	12.27	12.64	13.02
2	9.77	10.20	10.63	11.05	11.48	11.90	12.32	12.75	13.18	13.60	14.03	14.44	14.87
2½	11.00	11.48	11.95	12.43	12.91	13.39	13.86	14.34	14.82	15.30	15.78	16.26	16.74
3	12.22	12.75	13.28	13.81	14.34	14.87	15.40	15.94	16.47	17.00	17.53	18.06	18.59
3½	13.44	14.03	14.61	15.20	15.78	16.36	16.94	17.53	18.12	18.70	19.28	19.86	20.45
4	14.67	15.30	15.94	16.58	17.22	17.85	18.49	19.13	19.77	20.40	21.04	21.68	22.32
4½	15.88	16.58	17.27	17.95	18.65	19.34	20.03	20.72	21.41	22.10	22.79	23.48	24.17
5	17.10	17.85	18.60	19.34	20.08	20.83	21.57	22.32	23.05	23.80	24.55	25.30	26.04
5½	18.33	19.13	19.92	20.72	21.51	22.32	23.11	23.91	24.70	25.50	26.30	27.10	27.89
6	19.55	20.40	21.25	22.10	22.95	23.80	24.65	25.50	26.35	27.20	28.05	28.90	29.75
6½	20.77	21.68	22.58	23.48	24.39	25.29	26.19	27.10	28.00	28.90	29.80	30.70	31.61
7	21.99	22.95	23.91	24.87	25.82	26.78	27.73	28.68	29.64	30.60	31.56	32.52	33.47
7½	23.22	24.23	25.23	26.24	27.25	28.26	29.27	30.28	31.29	32.30	33.31	34.32	35.33
8	24.44	25.50	26.56	27.62	28.69	29.75	30.81	31.88	32.94	34.00	35.06	36.12	37.20
8½	25.66	26.78	27.90	29.01	30.12	31.22	32.35	33.48	34.59	35.70	36.81	37.93	39.05
9	26.88	28.05	29.22	30.39	31.56	32.72	33.89	35.06	36.23	37.40	38.57	39.74	40.91
9½	28.10	29.33	30.55	31.77	32.99	34.21	35.44	36.66	37.88	39.10	40.32	41.54	42.77
10	29.33	30.60	31.88	33.15	34.43	35.70	36.98	38.26	39.53	40.80	42.08	43.35	44.68
11	30.55	31.88	33.20	34.53	35.86	37.19	38.51	39.84	41.17	42.50	43.83	45.16	46.49
12	31.77	33.15	34.53	35.91	37.29	38.67	40.05	41.44	42.82	44.20	45.58	46.96	48.34
13	32.99	34.43	35.86	37.30	38.73	40.16	41.59	43.03	44.47	45.90	47.33	48.76	50.20
14	34.22	35.70	37.19	38.68	40.17	41.65	43.14	44.63	46.12	47.60	49.09	50.58	52.07
15	35.43	36.98	38.52	40.05	41.60	43.14	44.68	46.22	47.76	49.30	50.84	52.38	53.92
16	36.65	38.25	39.85	41.44	43.03	44.63	46.22	47.82	49.40	51.00	52.60	54.20	55.79
17	37.88	39.53	41.17	42.82	44.46	46.12	47.76	49.41	51.05	52.67	54.35	56.00	57.64
18	39.10	40.80	42.50	44.20	45.90	47.60	49.30	51.00	52.70	54.40	56.10	57.80	59.50

(Continued)

Flat Rolled Carbon Steel
Weight Per Lineal Ft. in Lb.
Width in In.

Thick- ness, in.	9	9½	9¾	9¾	10	10½	10¾	10¾	11	11½	11¾	11¾	12
$\frac{1}{16}$	1.913	1.965	2.019	2.078	2.135	2.178	2.232	2.284	2.338	2.39	2.44	2.497	2.55
$\frac{1}{8}$	3.826	3.931	4.037	4.144	4.250	4.356	4.463	4.569	4.676	4.78	4.88	4.99	5.10
$\frac{3}{16}$	5.74	5.90	6.06	6.22	6.38	6.54	6.70	6.86	7.02	7.17	7.32	7.49	7.65
$\frac{1}{4}$	7.65	7.86	8.08	8.29	8.50	8.71	8.92	9.14	9.34	9.57	9.78	10.00	10.20
$\frac{5}{16}$	9.56	9.83	10.10	10.36	10.62	10.89	11.16	11.42	11.68	11.95	12.22	12.49	12.75
$\frac{3}{8}$	11.48	11.80	12.12	12.44	12.75	13.07	13.39	13.71	14.03	14.35	14.68	14.99	15.30
$\frac{7}{16}$	13.40	13.76	14.14	14.51	14.88	15.25	15.62	15.99	16.36	16.74	17.12	17.49	17.85
$\frac{1}{2}$	15.30	15.73	16.16	16.58	17.00	17.42	17.85	18.28	18.70	19.13	19.55	19.97	20.40
$\frac{9}{16}$	17.22	17.69	18.18	18.65	19.14	19.61	20.08	20.56	21.02	21.51	22.00	22.48	22.95
$\frac{5}{8}$	19.13	19.65	20.19	20.72	21.35	21.78	22.32	22.75	23.38	23.91	24.44	24.97	25.50
$\frac{3}{4}$	21.04	21.62	22.21	22.79	23.38	23.96	24.54	25.13	25.70	26.30	26.88	27.47	28.05
$\frac{7}{8}$	22.96	23.59	24.23	24.86	25.50	26.14	26.78	27.42	28.05	28.68	29.33	29.97	30.60
$1\frac{1}{16}$	24.86	25.55	26.24	26.94	27.62	28.32	29.00	29.69	30.40	31.08	31.76	32.46	33.15
$1\frac{1}{8}$	26.78	27.52	28.26	29.01	29.75	30.50	31.34	31.98	32.72	33.47	34.21	34.95	35.70
$1\frac{1}{4}$	28.69	29.49	30.28	31.08	31.88	32.67	33.48	34.28	35.06	35.86	36.66	37.46	38.25
1	30.60	31.45	32.20	33.15	34.00	34.85	35.70	36.55	37.40	38.25	39.10	39.95	40.80
$1\frac{1}{16}$	32.52	33.41	34.32	35.22	36.12	37.03	37.92	38.83	39.74	40.64	41.54	42.45	43.35
$1\frac{1}{8}$	34.43	35.38	36.34	37.29	38.25	39.21	40.17	41.12	42.08	43.04	44.00	44.94	45.90
$1\frac{1}{4}$	36.34	37.35	38.36	39.37	40.38	41.39	42.40	43.40	44.42	45.42	46.44	47.45	48.45
$1\frac{3}{8}$	38.26	39.31	40.37	41.47	42.50	43.56	44.63	45.69	47.76	47.82	48.88	49.94	51.00
$1\frac{1}{2}$	40.16	41.28	42.40	43.52	44.64	45.75	46.86	47.97	49.08	50.20	51.32	52.44	53.55
$1\frac{5}{8}$	42.08	43.25	44.41	45.58	46.75	47.92	49.08	50.25	51.42	52.59	53.76	54.93	56.10
$1\frac{3}{4}$	44.00	45.22	46.44	47.66	48.88	50.10	51.32	52.54	53.76	54.99	56.21	57.43	58.65
$1\frac{7}{8}$	45.90	47.18	48.45	49.73	51.00	52.28	53.55	54.83	56.10	57.37	58.65	59.93	61.20
$2\frac{1}{16}$	47.82	49.14	50.48	51.80	53.14	54.46	55.78	57.11	58.42	59.76	61.10	62.43	63.75
$2\frac{1}{8}$	49.73	51.10	52.49	53.87	55.25	56.63	58.02	59.40	60.78	62.16	63.54	64.92	66.30
$2\frac{1}{4}$	51.64	53.07	54.51	55.94	57.38	58.81	60.24	61.68	63.10	64.55	65.98	67.42	68.85
$2\frac{3}{8}$	53.56	55.04	56.53	58.01	59.50	60.99	62.48	63.97	65.45	66.93	68.43	69.92	71.45
$2\frac{1}{2}$	55.46	57.00	58.54	60.09	61.62	63.17	64.70	66.24	67.80	69.33	70.86	72.41	73.90
$2\frac{5}{8}$	57.38	58.97	60.56	62.16	63.75	65.35	66.94	68.53	70.12	71.72	73.31	74.90	76.50
$2\frac{3}{4}$	59.29	60.94	62.58	64.23	65.88	67.52	69.18	70.83	72.46	74.11	75.76	77.41	79.05
3	61.20	62.90	64.60	66.30	68.00	69.70	71.40	73.10	74.80	76.50	78.20	79.90	81.60

(Concluded)

Temperature Conversion Data

The two temperature scales commonly used in metallurgical work are Fahrenheit and Centigrade. In the former the freezing of water is called 32° and its boiling point 212°; in the latter the freezing temperature of water is taken as 0° and the boiling point 100°. Thus 100 divisions (100-0) on the Centigrade scale are equivalent to 180 divisions (212-32) on the Fahrenheit scale or one Centigrade degree is 9/5 (180/100) of a Fahrenheit degree. Conversion from one scale to the other may be made quite readily by the following formulae based on the relations given above.

(a) Conversion from Fahrenheit (F.) to Centigrade (C.) : $C = 5/9 (F.-32)$.

(b) Conversion from Centigrade (C.) to Fahrenheit (F.) = $9/5 (C.) + 32$.

Problem—How many °F. are equivalent to 355°C.?

How many °C. are equivalent to 1505°F.?

In the first case use formula (b) which becomes

$$F = 9/5 (355) + 32 = 639 + 32 = 671$$

In the second case use formula (a) which becomes

$$C = 5/9 (1505-32) = 5/9 (1473) = 818.33$$

Temperature Conversion Table—Many tables and charts have been prepared for direct conversion from one temperature scale to the other, but they are, of necessity, quite large if direct readings to the nearest degree are given. A most useful small table¹ from which accurate conversions can be obtained is given on the next page. It will be noted that all Centigrade readings are given in heavy type; the figures in light type are Fahrenheit readings. The table gives direct readings at even 10°C. intervals from -270-3990°C. Conversions to the nearest degree are made by means of the "Interpolation Columns" at the right side of the page.

For example, to convert 355°C. to the Fahrenheit scale follow horizontally to the right from 300°C. in column 1 until under 50. The reading here is 662 and represents the equivalent in degrees Fahrenheit of 350°C. To find the equivalent of 355°C. which is 5°C. higher than the value we now have, obtain the Fahrenheit equivalent of 5°C. from the "Interpolation Column" at the upper right side of the page; this is 9°F. Add to 662°F., which gives 671°F. as the equivalent of 355°C.

Likewise, to find the equivalent on the Centigrade scale of 1505°F., locate the nearest number to this in the body of the main table. This is 1508°F. in the fourth column under the heading 20 and opposite 800. In other words, 1508°F. is equivalent to 820°C. The equivalent of 1505°F., or three degrees less, may be found by subtracting the equivalent of 3°F. (= 1.67°C.), obtained from the "Interpolation Column" at the lower right-hand side of the sheet, from 820°C. Thus 1505°F. equals 818.33°C.

¹Based on data prepared by Dr. Leonard Waldo, Metallurgical and Chemical Engineering.

Temperature Conversion Table

C°	0	10	20	30	40	50	60	70	80	90	Interpolation Columns
	F	F	F	F	F	F	F	F	F	F	
-200	-328	-346	-364	-382	-400	-418	-436	-454	....	....
-100	-148	-166	-184	-202	-220	-238	-256	-274	-292	-310	
-0	+ 32	+ 14	-4	-22	-40	-58	-76	-94	-112	-130	C° F° 1.... 1.8 2.... 3.6 3.... 5.4 4.... 7.2 5.... 9.0 6....10.8 7....12.6 8....14.4 9....16.2 10....18.0
0	32	50	68	86	104	122	140	158	176	194	
100	212	230	248	266	284	302	320	338	356	374	
200	392	410	428	446	464	482	500	518	536	554	
300	572	590	608	626	644	662	680	698	716	734	F° C° 1.... 0.56 2.... 1.11 3.... 1.67 4.... 2.22 5.... 2.78 6.... 3.33 7 ... 3.89 8 .. 4.44 9.... 5.00
400	752	770	788	806	824	842	860	878	896	914	
500	932	950	968	986	1004	1022	1040	1058	1076	1094	
600	1112	1130	1148	1166	1184	1202	1220	1238	1256	1274	
700	1292	1310	1328	1346	1364	1382	1400	1418	1436	1454	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
800	1472	1490	1508	1526	1544	1562	1580	1598	1616	1634	
900	1652	1670	1688	1706	1724	1742	1760	1778	1796	1814	
1000	1832	1850	1868	1886	1904	1922	1940	1958	1976	1994	
1100	2012	2030	2048	2066	2084	2102	2120	2138	2156	2174	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
1200	2192	2210	2228	2246	2264	2282	2300	2318	2336	2354	
1300	2372	2390	2408	2426	2444	2462	2480	2498	2516	2534	
1400	2552	2570	2588	2606	2624	2642	2660	2678	2696	2714	
1500	2732	2750	2768	2786	2804	2822	2840	2858	2876	2894	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
1600	2912	2930	2948	2966	2984	3002	3020	3038	3056	3074	
1700	3092	3110	3128	3146	3164	3182	3200	3218	3236	3254	
1800	3272	3290	3308	3326	3344	3362	3380	3398	3416	3434	
1900	3452	3470	3488	3506	3524	3542	3560	3578	3596	3614	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
2000	3632	3650	3668	3686	3704	3722	3740	3758	3776	3794	
2100	3812	3830	3848	3866	3884	3902	3920	3938	3956	3974	
2200	3992	4010	4028	4046	4064	4082	4100	4118	4136	4154	
2300	4172	4190	4208	4226	4244	4262	4280	4298	4316	4334	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
2400	4352	4370	4388	4406	4424	4442	4460	4478	4496	4514	
2500	4532	4550	4568	4586	4604	4622	4640	4658	4676	4694	
2600	4712	4730	4748	4766	4784	4802	4820	4838	4856	4874	
2700	4892	4910	4928	4946	4964	4982	5000	5018	5036	5054	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
2800	5072	5090	5108	5126	5144	5162	5180	5198	5216	5234	
2900	5252	5270	5288	5306	5324	5342	5360	5378	5396	5414	
3000	5432	5450	5468	5486	5504	5522	5540	5558	5576	5594	
3100	5612	5630	5648	5666	5684	5702	5720	5738	5756	5774	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
3200	5792	5810	5828	5846	5864	5882	5900	5918	5936	5954	
3300	5972	5990	6008	6026	6044	6062	6080	6098	6116	6134	
3400	6152	6170	6188	6206	6224	6242	6260	6278	6296	6314	
3500	6332	6350	6368	6386	6404	6422	6440	6458	6476	6494	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
3600	6512	6530	6548	6566	6584	6602	6620	6638	6656	6674	
3700	6692	6710	6728	6746	6764	6782	6800	6818	6836	6854	
3800	6872	6890	6908	6926	6944	6962	6980	6998	7016	7034	
3900	7052	7070	7088	7106	7124	7142	7160	7178	7196	7214	10.... 5.56 11.... 6.11 12.... 6.67 13.... 7.22 14.... 7.78 15.... 8.33 16.... 8.89 17.... 9.44 18....10.00
C°	0	10	20	30	40	50	60	70	80	90	

Fusing Points of Pyrometric Cones¹

Cone No.	When fired slowly 68°F. per hr. °F.	When fired rapidly 300°F. per hr. °F.	Cone No.	When fired slowly 68°F. per hr. °F.	When fired rapidly 300°F. per hr. °F.
022	1085	1121	1	2057	2120
021	1103	1139	2	2075	2129
020	1157	1202	3	2093	2138
019	1166	1220	4	2129	2174
018	1238	1328	5	2156	2201
017	1328	1418	6	2174	2246
016	1355	1463	7	2210	2282
015	1418	1481	8	2237	2300
014	1463	1526	9	2282	2345
013	1517	1580	10	2300	2381
012	1544	1607	11	2345	2417
011	1607	1681	12	2390	2435
010	1634	1643	13	2462	2462
09	1706	1706	14	2534	2552
08	1733	1742	15	2570	2615
07	1787	1814	16	2642	2669
06	1841	1859	17	2669	2687
05	1886	1904	18	2705	2714
04	1922	1940	19	2759	2768
03	1976	2039	20	2768	2786
02	2003	2057			
01	2030	2093			

Cone No.	When heated at 210°F. per hr. °F.	Cone No.	When heated at 210°F. per hr. °F.
23	2876	34	3200
26	2903	35	3245
27	2921	36	3290
28	2939	37	3308
29	2984	38	3335
30	3002	*39	3389
31	3056	*40	3425
32	3092	*41	3578
33	3173	*42	3659

¹Compiled by The Edward Orton, Jr. Ceramic Foundation, Columbus, Ohio Complete details are given in the J. Am. Ceramic Soc., Nov., 1926, v. 9, No. 11, p. 701.

*Heated at 1110°F. per hr.

The Greek Alphabet

Alpha	= A, α	= A, a	Nu	= N, ν	= N, n
Beta	= B, β	= B, b	Xi	= Ξ, ξ	= X, x
Gamma	= Γ, γ	= G, g	Omicron	= O, ο	= O, o
Delta	= Δ, δ	= D, d	Pi	= Π, π	= P, p
Epsilon	= Ε, ε	= E, e	Rho	= Ρ, ρ	= R, r
Zeta	= Ζ, ζ	= Z, z	Sigma	= Σ, σ	= S, s
Eta	= Η, η	= E, e	Tau	= Τ, τ	= T, t
Theta	= Θ, θ	= Th, th	Upsilon	= Υ, υ	= U, u
Iota	= Ι, ι	= I, i	Phi	= Φ, φ	= Ph, ph
Kappa	= Κ, κ	= K, k	Chi	= Χ, χ	= Ch, ch
Lambda	= Λ, λ	= L, l	Psi	= Ψ, ψ	= Ps, ps
Mu	= Μ, μ	= M, m	Omega	= Ω, ω	= O, o

Specific Heat of Gases

By J. H. G. Williams*

Air is a mechanical mixture of chemical elements and compounds, as follows: Oxygen, nitrogen, carbon dioxide, water vapor, traces of dust, and rare gases. Dry air is free of water vapor.

Saturated air contains the maximum amount of water vapor possible at any particular temperature and barometric pressure.

Atmospheric air usually contains an amount of moisture (water vapor) less than saturated air. The amount of moisture in atmospheric air relative to the amount of moisture in saturated air (humidity) is reported daily by the U. S. Weather Bureau, as well as the mean temperature and the barometric pressure.

Variations in the amount of moisture modify the specific heat of air, and, therefore, the specific heat of dry air at a given temperature should be corrected for the actual humidity condition.

The weight in lb. per cu. ft. of moist air is represented by the equation:

$$(a) \quad D = 1.326 \left\{ \frac{B}{T} \right\} - 0.501 \left\{ \frac{he}{T} \right\}$$

where

D = weight in lb. per cu. ft. of moist air at temperature T and relative humidity h

t = temperature of the air in °F.

T = absolute temperature = $t + 459.6$

B = barometric pressure in in. of mercury

h = relative humidity

e = pressure of saturated vapor corresponding to temperature t , in in. of mercury.

Problem—On July 6, 1923, the report of the U. S. Weather Bureau for Hartford at 8:00 a. m., was

Barometer 30; temperature 66, and humidity 92.

What was the specific heat of the air at 1500°F.?

Solution of Problem—The term $1.326/T$ in equation (a) can be obtained directly from Table II by dividing the figures given in column 6 by 1000. For 66°F. this equals 0.002523.

Likewise the term $0.501 e/T$ can be obtained from Table II by dividing the figures given in column 7 by 1000. For 66°F. this equals 0.000614.

Substituting in equation (a) we have:

$$D = 0.002523 \times 30 - 0.000614 \times 0.92 = 0.0751 \text{ lb. per cu. ft.}$$

This air consists of water vapor and dry air.

To find the weight of water vapor in the air, multiply the (relative) humidity by the weight of 1 cu. ft. of completely saturated vapor at the stated temperature (66°F.), as shown in Table I, and divide by 100, thus:

Pounds of water vapor per cu. ft. of air =

$$\frac{0.1001 \times 0.92}{100} = 0.0009$$

Now, we have

$$0.0751 - 0.0009 = 0.0742 \text{ lb. of dry air, and} \\ 0.0009 \text{ lb. of water vapor}$$

in our mixture at 66°F. Hence 1 lb. of the mixture should consist of:

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$$\frac{0.0742}{0.0751} \times 100 = 98.8\% \text{ dry air, and}$$

$$\frac{0.0009}{0.0751} \times 100 = 1.2\% \text{ water vapor}$$

The mean specific heat of air with any degree of saturation may be found by multiplying the weight of dry air by its specific heat and adding the product of the weight of water vapor by its specific heat and then dividing the sum by the total weight.

The mean specific heat of dry air at any temperature "t" is shown in column 3, Table III, to be equal to

$$0.240 + 0.0000051 \text{ t}$$

Likewise the mean specific heat of water vapor at any temperature "t" is shown to be equal to

$$0.459 + 0.000031 \text{ t}$$

Thus the specific heat at 1500°F. for

$$\text{dry air is } 0.240 + 0.0000051 \times 1500 = 0.2477$$

$$\text{water vapor is } 0.459 + 0.000031 \times 1500 = 0.5055$$

Since there are 98.8 parts of dry air and 1.2 parts of water vapor per 100 parts of moist air, the total mean specific heat of the mixture is equal to

$$\frac{0.2477 \times 98.8}{100} + \frac{0.5055 \times 1.2}{100} = 0.2508 + 0.0069 = 0.2577$$

Table I ⁽¹⁾

Weight of 100 Cubic Feet of Aqueous Vapor at Different Temperatures,
Completely Saturated

(Relative Humidity = 100)

Temp., °F.	Weight, Lb.	Temp., °F.	Weight, Lb.	Temp., °F.	Weight, Lb.	Temp., °F.	Weight, Lb.	Temp., °F.	Weight, Lb.
0	0.0069	24	0.0212	48	0.0543	72	0.1215	96	0.2518
1	0.0072	25	0.0222	49	0.0562	73	0.1235	97	0.2592
2	0.0075	26	0.0232	50	0.0582	74	0.1295	98	0.2667
3	0.0079	27	0.0242	51	0.0603	75	0.1337	99	0.2744
4	0.0083	28	0.0253	52	0.0625	76	0.1379	100	0.2824
5	0.0087	29	0.0265	53	0.0647	77	0.1423	101	0.2905
6	0.0091	30	0.0276	54	0.0669	78	0.1468	102	0.2988
7	0.0096	31	0.0289	55	0.0693	79	0.1514	103	0.3073
8	0.0101	32	0.0302	56	0.0716	80	0.1562	104	0.3161
9	0.0106	33	0.0314	57	0.0742	81	0.1611	105	0.3250
10	0.0111	34	0.0326	58	0.0767	82	0.1661	106	0.3242
11	0.0117	35	0.0338	59	0.0793	83	0.1712	107	0.3435
12	0.0122	36	0.0351	60	0.0821	84	0.1765	108	0.3531
13	0.0128	37	0.0364	61	0.0849	85	0.1819	109	0.3629
14	0.0134	38	0.0378	62	0.0877	86	0.1875	110	0.3730
15	0.0141	39	0.0392	63	0.0907	87	0.1932	115	0.4270
16	0.0147	40	0.0407	64	0.0938	88	0.1991	120	0.4874
17	0.0154	41	0.0422	65	0.0969	89	0.2051	125	0.5548
18	0.0161	42	0.0438	66	0.1001	90	0.2113	130	0.6300
19	0.0169	43	0.0454	67	0.1034	91	0.2176	135	0.7135
20	0.0176	44	0.0471	68	0.1069	92	0.2241	140	0.8061
21	0.0185	45	0.0488	69	0.1104	93	0.2308	150	1.0216
22	0.0194	46	0.0506	70	0.1140	94	0.2376	160	1.2826
23	0.0203	47	0.0524	71	0.1177	95	0.2446	170	1.5961

¹From the Chemist's Pocket Manual—Meade, page 125.

Table II ⁽¹⁾
Properties of Air Mixed with Water Vapor

Temp., t Mercury	Vapor Pressure In. of °F. °	Psi ,	Weight of water vapor per cu ft Grains Lb.	$\frac{1.326}{T} \times 1000$	$\frac{6}{T} \times 1000$
32	0.1804	0.0886	2 129	0.000304	2.697
34	0.1955	0.0960	2.297	0.000328	2.686
36	0.2117	0.1040	2.477	0.000354	2.676
38	0.2290	0.1125	2.669	0.000381	2.665
40	0.2477	0.1217	2.872	0.000410	2.654
42	0.2677	0.1315	3.091	0.000442	2.644
44	0 2891	0.1420	3.322	0.000475	2.633
46	0 3119	0 1532	3.570	0.000510	2.623
48	0 3366	0 1653	3 831	0 000547	2.612
50	0.3627	0 1781	4.110	0.000587	2 602
52	0 3905	0.1918	4.411	0.000630	2.592
54	0.4202	0.2064	4.720	0.000674	2.582
56	0.4518	0.2219	5.054	0.000722	2.572
58	0.4856	0.2385	5.410	0.000773	2.562
60	0.5217	0.2562	5.785	0.000827	2.552
62	0.5598	0.2749	6.043	0.000883	2.542
64	0.6005	0.2949	6.604	0.000943	2.532
66	0.644	0.3161	7.048	0.001007	2.523
68	0.689	0.3386	7.52	0.001074	2.513
70	0.738	0.3625	8.02	0.001145	2.504
72	0.789	0.3879	8.54	0.001220	2.494
74	0.844	0.4148	9.10	0.001300	2.485
76	0 903	0.4433	9.68	0.001383	2.476
78	0 964	0.4735	10.30	0.001471	2.466
80	1.029	0.5054	10.95	0.001564	2.457
82	1.098	0.539	11.64	0.001663	2.448
84	1.171	0.575	12.37	0.001768	2.439
86	1.248	0.613	13.15	0.001879	2.430
88	1.329	0.653	13.98	0.001997	2.422
90	1.415	0.695	14.85	0.002121	2.413
92	1.506	0.739	15.77	0.002253	2.404
94	1.602	0.787	16.74	0.002391	2.395
96	1.704	0.837	17.76	0.002537	2.387
98	1.812	0.890	18.79	0.002690	2.378
100	1.925	0.946	19.95	0.002850	2.370
102	2.044	1.004	21.12	0.003017	2.361
104	2.171	1.066	22.35	0.003193	2.353
106	2.303	1.131	23.63	0.003376	2.344
108	2.441	1.199	24.96	0.003566	2.336
110	2.588	1 271	26.36	0.003765	2.328
120	3.439	1.689	34.42	0.004916	.....
130	4.518	2.219	44.45	0.00635	.....
140	5.874	2.885	56.86	0.00812	.....
150	7.56	3.714	72.0	0.01029	.....
160	9.64	4.737	90.5	0.01293	.....
170	12.19	5.988	112.7	0.01611	.....
180	15.28	7.506	139.4	0.01991	.....
190	20.01	9.335	171.0	0.02443	.....
200	23.46	11.523	208.3	0.02976	.....
210	28.75	14.122	252.1	0.03601	.....
212	29.92	14.697	261.7	0.03738	.....

⁽¹⁾Mark's, Mechanical Engineers' Handbook.

Table III
Mean Specific Heats of Gases at Constant Pressure of One Atmosphere*
Temperatures up to 2000°C. (3600°F.)

Gas	Mean Specific Heat at Constant Pressure†	
	G. cal. per g. per °C, t = °C.	B.t.u. per lb. per °F, t = °F.
Hydrogen	3.39 + 0.000176t	3.39 + 0.000098t
Nitrogen	0.248 + 0.0000095t	0.248 + 0.0000053t
Oxygen	0.217 + 0.0000083t	0.217 + 0.0000046t
Water vapor.....	0.46 + 0.000055t	0.459 + 0.000031t
Carbon monoxide.....	0.248 + 0.0000095t	0.248 + 0.0000053t
Carbon dioxide.....	0.199 + 0.000038t	0.198 + 0.000021t
Air	0.240 + 0.0000092t	0.240 + 0.0000051t

Gas	G. cal. per cu.m. per °C., t = °C.	
	B.t.u. per cu.ft. per °F, t = °F.	
Hydrogen	305 + 0.0158t	0.0190 + 0.00000055t
Nitrogen	310 + 0.0119t	0.0194 + 0.00000041t
Oxygen	310 + 0.0119t	0.0194 + 0.00000041t
Water vapor.....	275 + 0.0328t	0.0171 + 0.00000116t
Carbon monoxide.....	310 + 0.0119t	0.0194 + 0.00000041t
Carbon dioxide.....	393 + 0.075t	0.0244 + 0.0000026t
Air	310 + 0.0119t	0.0194 + 0.00000041t

†Mean Specific Heat at Constant Pressure. Gas volumes at 1 atmosphere pressure and 0°C. (32°F.), except for water vapor for which the volume is at 100°C. (212°F.).

Mean Specific Heats per Cu.Ft., B.t.u. per Cu.Ft. per °F.

Temp., °F.	Nitrogen, Oxygen, Carbon		Carbon Dioxide‡	Water Vapor‡‡
	Monoxide, Air†			
100	0.0194	0.0247	.....
200	0.0195	0.0249	.....
300	0.0195	0.0252		0.0174
400	0.0196	0.0254		0.0176
500	0.0196	0.0257		0.0177
600	0.0196	0.0260		0.0178
700	0.0197	0.0262		0.0179
800	0.0197	0.0265		0.0180
900	0.0198	0.0267		0.0181
1000	0.0198	0.0270		0.0183
1100	0.0199	0.0273		0.0184
1200	0.0199	0.0275		0.0185
1300	0.0199	0.0278		0.0186
1400	0.0200	0.0280		0.0187
1500	0.0200	0.0283		0.0188
1600	0.0201	0.0286		0.0189
1700	0.0201	0.0288		0.0190
1800	0.0201	0.0291		0.0192
1900	0.0202	0.0293		0.0193
2000	0.0202	0.0296		0.0194

*Compiled by James B. Friauf, A. O. Smith Corp., Milwaukee.

†Volume of 1 cu.ft. measured at 1 atmosphere and 32°F. Mean c_p from 32°F. to temperature in first column

‡‡Volume of 1 cu.ft. measured at 1 atmosphere and 212°F. Mean c_p from 212°F. to temperature in first column.

Periodic Arrangement of the Elements—Mendeleeff's

Series	Period	Zero Group	Group I — R_2O	Group II — RO	Group III — R_2O_3	Group IV RH_4 RO_2	Group V RH_5 R_2O_5	Group VI RH_2 RO_3	Group VII RH R_2O_7	Group VIII
0										
1		Hydrogen H=1.0078 No. 1								
2	1	Helium He=4.002 No. 2	Beryllium Be=9.02 No. 3	Boron B=10.82 No. 5	Carbon C=12.00 No. 6	Nitrogen N=14.008 No. 7	Oxygen O=16.000 No. 8	Fluorine F=19.00 No. 9		
3	2	Neon Ne=20.183 No. 10	Sodium Na=22.997 No. 11	Aluminum Al=26.97 No. 13	Silicon Si=28.06 No. 14	Phosphorus P=31.02 No. 15	Sulphur S=32.06 No. 16	Chlorine Cl=35.457 No. 17		
4	3	Argon Ar=39.944 No. 18	Potassium K=39.10 No. 19	Calcium Ca=40.08 No. 20	Scandium Sc=45.10 No. 21	Titanium Ti=47.90 No. 22	Vanadium V=50.95 No. 23	Chromium Cr=52.01 No. 24	Manganese Mn=54.93 No. 25	Iron Fe=55.84 No. 26
5	4	Copper Cu=63.57 No. 29	Zinc Zn=65.38 No. 30	Gallium Ga=69.72 No. 31	Germanium Ge=72.60 No. 32	Arsenic As=74.93 No. 33	Selenium Se=78.96 No. 34	Bromine Br=79.916 No. 35		Cobalt Co=58.94 No. 27
6	5	Krypton Kr=83.9 No. 36	Rubidium Rb=85.44 No. 37	Strontium Sr=87.63 No. 38	Yttrium Y=88.92 No. 39	Zirconium Zr=91.22 No. 40	Columbium Cb=93.3 No. 41	Molybdenum Mo=96.0 No. 42	Ruthenium Ru=101.7 No. 44	Nickel Ni=58.89 No. 28
7	6	Silver Ag=107.880 No. 47	Cadmium Cd=112.41 No. 48	Indium In=114.8 No. 49	Tin Sn=118.70 No. 50	Antimony Sb=121.76 No. 51	Tellurium Te=127.5 No. 52	Iodine I=126.932 No. 53	Rhodium Rh=102.91 No. 45	Palladium Pd=106.7 No. 46
8	7	Xenon Xe=130.2 No. 54	Cesium Cs=132.81 No. 55	Barium Ba=137.36 No. 56	Lanthanum La=138.90 No. 57	Cerium Ce=140.13 No. 58				
9										
10										
11	6	Gold Au=197.2 No. 79	Mercury Hg=200.61 No. 80	Thallium Tl=204.39 No. 81	Lead Pb=207.22 No. 82	Bismuth Bi=209.00 No. 83				
12	7	Radon Rn=222 No. 86	Radium Ra=225.97 No. 88		Thorium Th=232.12 No. 90		Tungsten W=184.0 No. 74	Rhenium Re=186.31 No. 75	Osmium Os=190.8 No. 76	Iridium Ir=193.1 No. 77
		Elements not classified in the table above:								
		Praseodymium Pr=140.92 No. 59	Neodymium Nd=144.27 No. 60	Gadolinium Gd=157.3 No. 64	Europium Eu=152.0 No. 63	Holmium Ho=163.5 No. 67	Erbium Er=167.4 No. 68	Thulium Tm=169.4 No. 69	Ytterbium Yb=173.5 No. 70	Lutetium Lu=175.0 No. 71

The Crystal Structure of Metals and Alloys*

By Kent R. Van Horn†

The various elements crystallize according to a definite pattern or symmetrical arrangement of atoms that is repeated at regular intervals to form a section of any size. The three dimensional lattice-work of imaginary lines connecting the atoms is called a space lattice. The smallest parallelepiped which possesses the full symmetry of the crystal is termed the unit cell. The type and dimensions of the unit cells of most elements have been determined and tabulated in X-ray books^{1, 2, 3, 4, 5} or summarized on page 78.

There are only 14 types of space lattices possible and they fall into the seven crystal systems, cubic, tetragonal, hexagonal, rhombohedral, orthorhombic, monoclinic and triclinic. The crystal systems are defined in the Glossary of X-ray terms on page 11. The large majority of the metals crystallize according to three of the fourteen space lattices, the face-centered and body-centered of the cubic

Periodic table showing chemical elements with crystal structures of high symmetry. The table is organized into groups I through VIII at the top. Elements are grouped by crystal structure: Hexagonal Close-Packed (HCP), Body-Centered Cubic (BCC), and Face-Centered Cubic (FCC). The table includes atomic numbers and element symbols.

Group	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII
1	(1) H																	(2) He
2	He	(3) Li	(4) Be															(10) Ne
3	Ne	(11) Na	(12) Mg															(18) Ar
4	A	(19) K	(20) Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br
5	Kr	(37) Rb	(38) Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
6	Xe	(55) Cs	(56) Ba	(57-71) Rare Earths	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At
7		(87) Fr	(88) Ra	Ac	Th	Pa	U											
		(89) La	(90) Ce	Pr	Nd													
		(91) Th	(92) U															
		(93) Np	(94) Pu															
		(95) Am	(96) Cm															
		(97) Bk	(98) Cf															
		(99) Es	(100) Fm															
		(101) Md	(102) No															
		(103) Lr	(104) Rf															
		(105) Db	(106) Sg															
		(107) Bh	(108) Hs															
		(109) Mt	(110) Ds															
		(111) Nh	(112) Fl															
		(113) Nh	(114) Fl															
		(115) Nh	(116) Fl															
		(117) Nh	(118) Fl															
		(119) Nh	(120) Fl															

Legend:

- Hexagonal Close-Packed
- Body-Centered Cubic
- Face-Centered Cubic

Fig. 1—Periodic table showing the chemical elements having crystal structures of high symmetry.

system and the close-packed type of the hexagonal system. These three space lattices will be described in detail.

A periodic table of the elements is reproduced in Fig. 1 with the inert gases, and the metals beryllium and magnesium appearing twice to complete the symmetry of the arrangement. The number in the periodic system is indicated above each member of Group I and above the last element occurring on any horizontal line. The numerous elements crystallizing in the face-centered cubic, body-centered cubic, and hexagonal close-packed lattices are enclosed by characteristic markings. All polymorphic modifications having any of these three simple atomic arrangements are indicated by additional outlines (Fe, Co, Ti, etc.). The complex structures are not given. The majority of the metals which generally have one (or more when there are polymorphic modifications) of the three lattices of high symmetry appear at the left and the central part of the table. The nonmetallic elements, excepting the inert gases of Group VIII, are located at the extreme right of the table and have more complicated unit cells.

Since a high degree of crystalline symmetry, for example, face-centered cubic, body-centered cubic, and hexagonal close-packed arrangements, imparts the degree

*Revised section of the paper on "The Constitution of Alloys" by Kent R. Van Horn from the Symposium on Radiography and X-Ray Diffraction Methods, A.S.T.M., 1937.

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of plasticity and other important properties enjoyed by metals, these typical structures will be briefly described. The plasticity of metals is generally attributed to movements in certain directions along specific crystallographic planes, all the atoms in one series of planes moving as a block relative to a similar series of parallel planes. The planes of easiest slip generally possess the greatest atomic concentration and the associated characteristic of a large distance between the intervening planes (interplanar distance). The latter feature implies that the restraining forces acting between consecutive planes will be a minimum. Also, slip within the favorite planes proceeds most easily along the atomic rows of highest density. It is the flowing or

gliding movement along these planes of atoms in specific directions which permits a solid metal to alter its external form. The three lattices of high atomic symmetry have more densely populated planes and lines of atoms than the complex structures. The three simple atomic arrangements also exhibit different degrees of plasticity, for example, metals crystallizing in the hexagonal close-packed system are generally less ductile than those of the face-centered cubic lattice.

Face-Centered Cubic Structure—

A more concrete picture of the familiar metal structures may be obtained from Fig. 2, 3 and 4 which were reproduced from Hume-Rothery's interesting treatise on alloys.* Fig. 2(a) shows the face-centered cubic unit cell with an atom located in each corner and center of each face of the cube. Fig. 2(b) illustrates the same configuration repeated for a number of cells but the atoms are represented by spheres in contact. This type of lattice is termed "close-packed" because the most intimate possible association of the spheres results. Although Fig. 2(b) more nearly typifies the manner

Fig. 2—Face-centered cubic structure. (a) Face-centered cubic unit cell. (b), (c), (d) Face-centered cubic packing of spheres in contact* (e) X-ray photograph of face-centered cubic copper. Mo-K α radiation.

in which the atoms exist in metals compared to the voids suggested by Fig. 2(a), it should not be inferred that an atom is a hard ball of specific dimensions. If the atom marked with a dot is removed from a corner of a cube of Fig. 2(b), the arrangement of Fig. 2(c) is obtained, exposing a plane of six spheres (appearing lighter in the illustration), lines through the centers of which form equilateral triangles. Fig. 2(d) shows the arrangement on this plane more clearly after the above six spheres are extracted. The same operation could be initiated from any of the corners of a cube, thereby uncovering eight similar close-packed planes in which each atom is at the center of a hexagon formed by lines through the centers of its six equidistant neighbors. The eight planes would form the faces of an octahedron if extended and are called the octahedral or $\{111\}$ planes.* There are only four series of $\{111\}$ planes as the opposite faces of the octahedron are parallel. The three rows of close atom packing on the $\{111\}$ planes are the sides of the equilateral triangles or $[110]$ directions which are the normals to the faces of the regular dodecahedron. The face-centered cubic lattice has, therefore, four close-packed planes $\{111\}$ and twelve close-packed directions $[110]$ which is the highest degree of atomic concentration and symmetry encountered in any crystal structure. Consequently, the metals of this type such as aluminum, copper, and silver are ductile, easily deformed, and are good conductors of heat or electricity. The X-ray pattern characteristics of this space lattice is included as Fig. 2(e).

Body-Centered Cubic Structure—The body-centered cubic unit cell has an atom at each corner and one in the center of the cube as illustrated in Fig. 3(a) and

* $\{111\}$ denotes the Miller indices which are the symbols of a crystallographic system for identifying the planes in space. (See page 14.)

represented by spheres in contact in Fig. 3(b).⁶ The low concentration of atoms, compared to Fig. 2(b), suggests that this structure is not one of most intimate atomic association. If the two spheres (marked by dots) of the nearest cube edge of Fig. 3(b) are removed, the result is shown in Fig. 3(c). The plane exposed is that containing the most atoms for this space lattice, namely, the cube diagonal or dodecahedral $\{110\}$ of which there are six sets. The large voids or interstices between the atoms signify that this plane is not one of close-packing compared to the face-centered cubic $\{111\}$ planes. Therefore, the body-centered cubic metals do not have a well defined slip plane but may deform by movement along various planes $\{110\}$, $\{112\}$, $\{123\}$ dependent on the relations of stress and the important directions $[111]$. Fig. 3(c) exhibits close-packed lines of atoms, the diagonal $[111]$ rows, which are normal to the four sets of octahedral $\{111\}$ planes. This condition

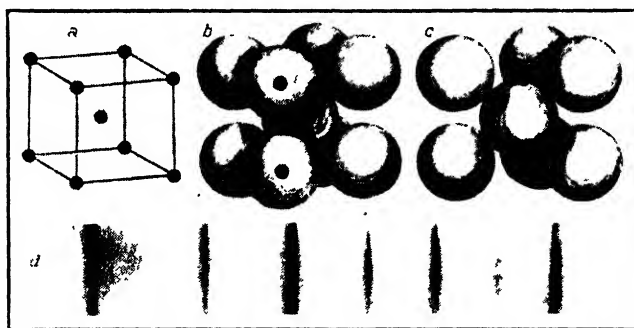


Fig. 3—Body-centered cubic structure. (a) Body-centered cubic unit cell. (b), (c) Body-centered cubic packing of spheres in contact.⁶ (d) X-ray photograph of body-centered cubic iron. MoK α radiation.

(no close-packed planes and only four close-packed directions) does not impart a high degree of plasticity⁷ and the metals of this class such as alpha iron, molybdenum, or tungsten, have great strength, high melting points and medium ductility. The X-ray pattern characteristic of this structure is illustrated in Fig. 3(d).

Hexagonal Close-Packed Structure—The close-packed hexagonal unit cell is depicted in Fig. 4(a) which is redrawn according to the conventional spheres in contact in Fig. 4(b). The close-packed arrangement approaches that of Fig. 2(b). The lower and upper horizontal planes of spheres exhibit the hexagonal grouping of one atom intimately surrounded by six neighbors. These planes of high atomic concentration are the basal faces $\{0001\}$ and the lines of close-packing on these planes are parallel to the edges of the first order prism faces $\{1010\}$. As the opposite faces of the hexagon are parallel, there is one close packed series of planes $\{0001\}$ and three important rows $[1010]$. Consequently it is to be expected that slip may proceed along specific planes in certain directions in this structure but not with the freedom of the face-centered cubic lattice (four planes, twelve directions). The hexagonal elements such as cadmium, magnesium, or zinc may accommodate their structure to stress by another mechanism, twinning, which alteration generates new additional slip planes $\{0001\}$ thereby approximating the plasticity characteristic of face-centered cubic metals and surpassing that of the body-centered cubic metals. The X-ray pattern characteristic of the close-packed hexagonal cell is represented in Fig. 4(c). Elements crystallizing with lower symmetry than the face-centered cubic, body-centered cubic, and hexagonal close-packed arrangements such as orthorhombic, monoclinic, or triclinic do not possess the close-packed planes and directions of slip or deformation. They are therefore relatively brittle and are not used as extensively as the more plastic metals.

Polymorphic Modifications of Metals—When a mineral or chemical compound crystallizes in two or more different forms, it is called polymorphic. Frequently the prefixes "di" or "tri" are used to denote the number of modifications if there are two or three. Metals which occur in two or more forms characterized by either different crystal structures or marked differences in energy content or both are generally called allotropic. The terminology has been the source of confusion as allotropy has been interpreted by some to represent a reversible change of a physical property

while others consider allotropy to be equivalent to polymorphism involving only an alteration in atomic arrangement. The disturbing effects of impurities frequently cause variations in physical properties which might be erroneously interpreted as a significant change by the former conception. Although allotropy may be more frequently considered to denote a crystal structure transformation, it seems advisable to use "polymorphism" so there will be no doubt as to the nature implied.

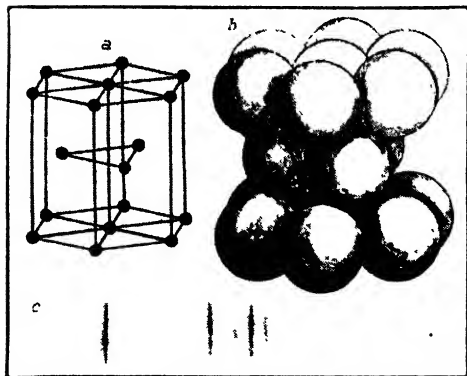


Fig. 4—Hexagonal close-packed structure, (a), (b) Close-packed hexagonal unit cell and packing of spheres in contact.⁶ (c) X-ray photograph of close-packed hexagonal zinc. Mo-K α radiation.

The much discussed phase change from α to γ iron at 1668°F. (909°C.), on heating, is the basis of steel heat treating. For a considerable period of time there were supposed to be four different structural forms, namely, α , β , γ and δ iron. However, X-ray analysis has established the nature of the transformations by the examination of pure electrolytic iron at elevated temperatures in a specially designed camera.⁸ It now appears that the so-called " β " iron is not a unique modification, that α and δ have the same structure and that pure iron therefore exists in only two different crystal forms corresponding to two polymorphic transformations, $\alpha \rightleftharpoons \gamma$ at A_1 , and $\gamma \rightleftharpoons \delta(\alpha)$ at A_4 . Pure α iron is body-centered cubic while the γ form has a face-centered cubic structure. X-ray analysis is a very reliable and convenient method for investigating polymorphic transformations at room or elevated temperatures.

Alloy Structures—When two metals are melted together and then solidified, a number of different structures may result. The various types are derived from the degree of mutual solubility of the component metals, their ability to combine or form intermediate phases, and the effect of temperature on these tendencies. The structural types which two elements may assume in the solid are graphically represented by constitutional diagrams, page 388, and are characterized by: (1) elements or metals; (2) solid solutions; (3) intermediate phases; and (4) superlattices.

A metal may occur in an alloy system where one metal is immiscible in the solid state in the other metal. The three symmetrical atomic arrangements typical of the common metals are illustrated in Fig. 2, 3 and 4. If the metal is not polymorphic, the same crystal structure will exist up to the melting point.

A solid solution of two or more metals is defined as a phase in which the crystal lattice of one component is retained. This would include continuous solid solutions and restricted solutions such as the end (terminal) phases of diagrams exhibiting immiscible regions (eutectic) and intermediate phases. Solid solutions, either complete or partial, may be divided into two types: The general or substitutional class, and the more limited interstitial group. When the solute atoms replace or are substituted for some of the atoms of the solvent lattice, the solution is termed substitutional. In the second, or interstitial type, the solute atoms are dispersed in the vacant spaces between the solvent atoms, that is introduced in the lattice in addition to the solvent atoms. The interstitial solutions occur infrequently and are confined to systems where the diameter of a solute atom is appreciably

Precision X-ray investigations of the elements have disclosed at least fifteen metals (beryllium, calcium, cerium, cobalt, iron, lanthanum, manganese, nickel, rhodium, thallium, tin, tungsten, uranium and zirconium) to exist in two or more different crystal forms. The names of the polymorphs, the type of space lattice, and the temperature range of stability have been tabulated.⁷ In addition to the metals, carbon, oxygen, nitrogen, phosphorus, selenium and sulphur have polymorphic modifications. The elements arsenic, antimony, bismuth, erbium, neodymium, praseodymium, ruthenium and possibly silver and strontium may be polymorphic.

The classic example of polymorphism is the transition of metallic white tin to the gray powder at 18°C., frequently called the tin pest. The white type is tetragonal and the gray tin variety, diamond cubic.

smaller than that of the solvent atom. Boron, carbon, and nitrogen are prone to form interstitial solutions with the transition elements, for example, carbon in γ iron (austenite).

Substitutional solutions may contract or expand the dimensions of the solvent metal cell depending on the size of the replacing solute atoms. An interstitial solution always enlarges the solvent lattice. The above discussion of the structures of metals would apply to solid solutions in as much as their crystal structures are generally simple and are similar to at least one of the component metals.

Intermediate phases are frequently referred to as "intermetallic compounds" or solid solutions, depending on certain phenomena and preference of definitions. It has been difficult in the past with the older methods of determining constitutional data to define the limits where a solid solution begins and a compound terminates. No satisfactory classification of intermediate phases was evolved until the advent of X-ray analysis. Now the term intermediate phase is used to denote those products of intermetallic reactions of two or more elements having a different space lattice from any of the components.* An intermediate phase may have a restricted or extended range of homogeneity. A variable composition is obtained by a change in the numerical atomic ratios of the elements composing the phase effected generally by atomic substitutions and infrequently by interstitial additions. In several instances two atoms, or a chain of atoms, replace a single atom in a substitutional region of an intermediate phase. The crystal structures of some intermediate phases are simple (Fig. 2-4), but many crystallize in complex arrangements which could not be adequately described in the allotted space.

A new structural arrangement called a superlattice has recently been discovered. There has been much discussion as to the classification of a superlattice structure such as a solid solution, intermediate phase, or "intermetallic compound." As this formation may occur in a homogeneous alloy with no appreciable alteration in the crystal structure, a superlattice may best be considered to be a modification of a solid solution or an intermediate phase, depending on the parent arrangement.

A substitutional solid solution exhibits, in most cases, a random or disordered distribution of the solute and solvent atoms in the solvent cells. However, some solid solutions when slowly cooled, or annealed at low temperatures, possess definite ordered positions of both atoms in the solvent space lattice (superlattice). This resorting of atoms may occur in a solid solution when two elements, A and B, exist in concentrations approximately represented by the formulas AB and A_2B such as CuAu, Cu₃Au, Cu₃Pd. Also intermediate phases of variable compositions in the range of the same atomic proportions as above may experience an order-disorder change, as the β phase CuZn. Superlattice formations may be accompanied by marked variations in physical properties such as specific heat and electrical resistivity.

It would appear that the ordered distribution is the stable condition at low temperatures in the susceptible compositions because the atoms meshed together with a lower degree of internal energy than in one of disorder. At high temperatures where the alloy is less rigid, thermal movements tend to shuffle the atoms into random positions. The transition is not so abrupt as transformations involving a phase change, but gradual so that many intermediate stages may be encountered. X-ray methods can accurately follow the process in either direction as the ordered atoms give diffraction effects in addition to the reflections characteristic of the parent lattice. The intensities of the extra superlattice lines progressively decrease as the ordering diminishes, becoming fainter, and finally the lines vanish when the disordered distribution is attained.

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*In a few systems intermediate phases have the same type of structure as a component but appreciably different parameters.

Physical Constants of Elements*

Introduction—The following table has been compiled from the best available sources and checked by about fifty specialists on the various elements. While the data are believed to be accurate, certain generalizations have been necessary for tabulation and should, therefore, be used only for general purposes and comparison

Elements	Symbol	Atomic No.	Atomic Weight (1938)	Density, g./cm. ³ at 20°C. (68°F.)	Density, lb./in. ³ at 68°F. (20°C.)	Atomic Volume, cm. ³ /g. Atom	Melting Point, °F.	Boiling Point, °F. (760 mm. Pressure)	Specific Heat, cal./g./°C. at room temperature equals B.t.u./lb./°F. at room temperature	Latent Heat of Fusion, cal./g.	Latent Heat of Fusion, B.t.u./lb.
Actinium	Ac	89	227				3272 ^d	>3092 ^d			
Aluminum	Al	13	26.97	2.70	0.0975	9.99	1214.6	3733	0.2259	93	167.4
Antimony	Sb	51	121.76	6.02	0.2391	18.39	1166.9	2624	0.0493	38.26	68.87
Argon	A	18	39.944	1.6626x10 ⁻⁴	6.008x10 ⁻⁴		-306.2	-302.4	0.1252	6.71	12.08
Arsenic	As	33	74.91	5.73	0.2070	13.07	1497 ^d	1139 ^d	0.0822		
Barium	Ba	56	137.36	3.5	0.1265	39.25	1562	2980	0.0680		
Beryllium	Be	4	9.02	1.85	0.0658	4.96	2345	5036	0.425	345.5	621.9
Bismuth	Bi	83	209.00	9.80	0.3541	21.33	519.8	2642	0.0290	12.46	22.43
Boron	B	5	10.82	2.3	0.0831	4.70	4172	4622	0.3091		
Bromine	Br	35	79.916	3.12	0.1127	25.62	19.04	137.79	0.0703	16.15	29.07
Cadmium	Cd	48	112.41	8.65	0.3125	12.99	609.6	1412.6	0.0547	13.17	23.71
Calcium	Ca	20	40.08	1.55	0.0560	25.86	1664	2709	0.157		
Carbon (graphite)	C	6	12.01	2.22	0.0802	5.41		8721	0.165		
Cerium	Ce	58	140.13	6.9	0.2493	20.3	1427	2552	0.05		
Cesium	Cs	55	132.91	1.9	0.0686	69.95	78.8	1238	0.0521	3.76	6.77
Chlorine	Cl	17	35.457				-150.88	-30.28	0.226	22.97	41.35
Chromium	Cr	24	52.01	7.14	0.2579	7.29	2822	4500	0.12	31.75	57.15
Cobalt	Co	27	58.94	8.9	0.3216	6.6	2714	5252	0.0989	58.38	105.08
Columbium	Cb	41	92.91	8.57	0.3096	10.8	3542	>5972			
Copper	Cu	29	63.57	8.94	0.323	7.11	1981.4	4703	0.0918	50.6	91
Dysprosium	Dy	66	162.46								
Erbium	Er	68	167.2								
Europium	Eu	63	152.0								
Fluorine	F	9	19.00				-369.4	-304.6		10.06	18.1
Gadolinium	Gd	64	156.9								
Gallium	Ga	31	69.72	5.91	0.2135	11.8	85.6	3760	0.0788	19.16	34.5
Germanium	Ge	32	72.60	5.36	0.1937	13.54	1757.3	4892	0.0733		
Gold	Au	79	197.2	19.3	0.6973	10.22	1945.4	5371	0.0308	16.11	28.99
Hafnium	Hf	72	178.6	11.4	0.4118	15.66	3092	9740			
Helium	He	2	4.003	0.1664x10 ⁻⁴	0.6008x10 ⁻⁴		<-458.0	-452.0	1.25		
Holmium	Ho	67	163.5								
Hydrogen	H	1	1.0081	0.08375x10 ⁻⁴	0.3026x10 ⁻⁴		-434.4	-422.957	3.415	15.0	27.0
Indium	Ind	61									
Indium	In	49	114.76	7.31	0.264	15.7	322	>2642	0.0568		
Iodine	I	53	126.92	4.93	0.178	25.7	236.3	363.8	0.0523	15.76	28.40
Iridium	Ir	77	193.1	22.4	0.809	8.6	4368	8852	0.0322		
Iron	Fe	26	55.84	7.87	0.284	7.1	2795	5430	0.1075	65	117
Krypton	Kr	36	83.7	3.488x10 ⁻⁴	3.502x10 ⁻⁴		-275.22	-250.6			
Lanthanum	La	57	138.92	6.15	0.222	22.6	1518.8	3272	0.0446		

(Continued)

* This table was compiled by the Subcommittee on Physical Constants. The membership of the subcommittee was as follows: R. L. Kenyon, Chairman; J. B. Johnson, H. W. Russell, and C. S. Barrett.

The subcommittee solicits additional data and corrections for future revisions of this table. Communications should be directed to J. E. Donnellan, Sec. of the Committee, 7016 Euclid Ave., Cleveland.

between elements. In general, the data are as published in the various sources from which they were selected.

The articles in this Handbook which deal with the individual elements should be consulted for more complete information, especially regarding minor variations and effect of special treatments on the properties listed.

Linear Coefficient of Thermal Expansion / °C. at Room Temperature	Linear Coefficient of Thermal Expansion / °F. at Room Temperature	Thermal Conductivity, cal/cm ² /cm. ² /°C./sec. at Room Temperature	Electrical Resistivity, Microhm-cm	Modulus of Elasticity (Tension), psi.	Type of Crystal Lattice	Lattice Constant (A = 10 ⁻⁸ cm.) 20°C. (68°F.)			Closest Approach of Atoms, Å	Elements
						a ₁	b ₁	c ₁		
×10 ⁻⁶	×10 ⁻⁶			×10 ⁸						
24	13.3	0.52	2.655	10	Face-Centered Cubic	4.0413			2.858	Actinium
11.29	6.27	0.0444	39	11.3	Rhombohedral Hexagonal	4.4974	57°6'		2.878	Aluminum
		0.406×10 ⁻⁴								Antimony
3.86	2.14		35		Rhombohedral Hexagonal*	4.135	54°75'		2.50	Argon
					Body-Centered Cubic*	5.015			4.34	Arsenic
12.3	6.8	0.3847	18.5	42.7	Hexagonal Close Packed*	2.281	3.577		2.22	Barium
13.45	7.47	0.0200	115	4.6	Rhombohedral Hexagonal	4.736	57°14'		3.104	Beryllium
2	1.1		1.8×10 ¹²		Hexagonal (?)*					Bismuth
										Boron
29.8	16.6	0.217	7.59		Hexagonal Close Packed	2.9727	5.6061		2.972	Bromine
25	13.89		4.6		Face-Centered Cubic*	5.560			3.93	Cadmium
1.2	0.67	0.057	1000	0.7	Hexagonal*	2.46	6.69		1.42	Calcium
			78		Face-Centered Cubic*	5.143			3.64	Carbon (graphite)
97	54		20		Body-Centered Cubic	6.2			5.3	Cerium
11.44	6.36	0.172×10 ⁻⁴	10×10 ¹⁶							Cesium
8.1	4.5	0.165	13.1		Body-Centered Cubic*	2.878			2.492	Chlorine
12.08	6.71	0.165	9.7		Hexagonal Close Packed*	2.507	4.072		2.50	Chromium
7.2	4		20		Body-Centered Cubic	3.2941			2.852	Cobalt
16.42	9.1	0.023	1.682	16	Face-Centered Cubic	3.6080			2.551	Columbium
										Copper
					Hexagonal Close Packed*	3.74	6.09		3.74	Dysprosium
										Erbium
										Europium
										Fluorine
										Gadolinium
18.3	10.2		57.1		One-Face-Centered Orthorhombic	4.506	4.506	7.642	2.447	Gallium
			89×10 ³		Cubic (Diamond)	5.647			2.44	Germanium
14.4	8.0	0.7072	2.42	11.3	Face-Centered Cubic	4.0700			2.878	Gold
					Hexagonal Close Packed*	3.200	5.077		3.14	Hafnium
		3.32×10 ⁻⁴								Helium
										Holmium
		4.06×10 ⁻⁴								Hydrogen
										Illium
33	18.3	0.057	9		Face-Centered Cubic	4.585	4.941		3.24	Iodine
93	51.7	10.4×10 ⁻⁴	1.3×10 ¹⁶		One-Face-Centered Orthorhombic	4.791	7.248	9.771	2.70	Iridium
6.41	3.5	0.141	6.08	7.47×10 ⁷	Face-Centered Cubic	3.8312			2.709	Iron
11.9	6.6	0.19	9.8	30	Body-Centered Cubic*	2.8610			2.478	Krypton
		0.212×10 ⁻⁴								Lanthanum
			59		Hexagonal Close Packed*	3.75	6.06		3.7	

*See page 81 for footnote.

(Continued)

Elements	Symbol	Atomic No.	Atomic Weight (1938)	Density, g./cm. ³ at 20°C. (68°F.)	Density, lb./in. ³ at 68°F. (20°C.)	Atomic Volume, cm. ³ /g. Atom	Melting Point, °F.	Boiling Point, °F. (760 mm. Pressure)	Specific Heat, cal./g./°C. Specific Heat, B.t.u./lb./°F. at Room Temperature	Latent Heat of Fusion, cal./g.	Latent Heat of Fusion, B.t.u./lb.
Lead	Pb	82	207.21	11.34	0.409	18.3	621.2	3171	0.030	6.26	11.27
Lithium	Li	3	6.940	0.53	0.0193	13.1	366.8	2502	0.79	32.81	59.02
Lutecium	Lu	71	175.0								
Magnesium	Mg	12	24.32	1.74	0.0628	14.0	1204	2025	0.249	70.0	126
Manganese	Mn	25	54.93	7.44	0.268	7.4	2268	3904	0.107	64.8	116.64
Masurium	Ma	43									
Mercury	Hg	80	200.61	13.55	0.489	14.8	-38.0	674.4	0.0332	2.66	4.78
Molybdenum	Mo	42	95.95	10.2	0.368	9.4	4748	8679	0.0647		
Neodymium	Nd	60	144.27	7.05	0.255	20.5	1544		0.0447		
Neon	Ne	10	20.183	0.8387x10 ⁻³	3.030x10 ⁻⁴		-415.498	-411.34			
Nickel	Ni	28	58.69	8.9	0.322	6.64	2646	5252	0.112	73.8	132.8
Nitrogen	N	7	14.008	1.1649x10 ⁻³	4.209x10 ⁻⁴		-345.87	-320.40	0.247	6.15	11.07
Osmium	Os	76	190.2	22.5	0.812	8.45	4892	9920	0.031		
Oxygen	O	8	16.0000	1.3318x10 ⁻³	4.8122x10 ⁻⁴		-361.12	-297.334	0.2184	3.32	5.98
Palladium	Pd	46	106.7	12.0	0.433	8.9	2831	7196	0.0587	34.2	61.8
Phosphorus (Yellow)	P	15	31.02	1.82	0.0657	17.0	111.4	536	0.177	5.04	9.07
Platinum	Pt	78	195.23	21.45	0.774	9.1	3224	7933	0.0319	27.1	48.78
Polonium	Po	84									
Potassium	K	19	39.098	0.86	0.031	45.5	144.1	1425	0.177	1.5	26.1
Praseodymium	Pr	59	140.92	6.63	0.239	21.3	1724		0.458		
Protoactinium	Pa	91	231								
Radium	Ra	88	226.05	5.0	0.1808	45.2	1760	2084			
Radon	Rn	86	222	4.40*	0.159	50.45	-95.8	-79.2			
Rhenium	Re	75	186.31	20	0.723	8.9	5432	10,600	0.0346		
Rhodium	Rh	45	102.91	12.44	0.449	8.23	3571	8132	0.0598		
Rubidium	Rb	37	85.48	1.53	0.0553	55.87	101	1292	0.0802	6.095	10.75
Ruthenium	Ru	44	101.7	12.2	0.441	8.33	4442	8852	0.061		
Samarium	Sm	62	150.43	7.7	0.28	19.4	>2400				
Scandium	Sc	21	45.10	2.5	0.09	18.0	2200	4400			
Selenium	Se	34	78.96	4.81	0.174	16.4	428	1270	0.084		
Silicon	Si	14	28.06	2.4	0.087	11.7	2600	4149	0.1762		
Silver	Ag	47	107.880	10.5	0.38	10.27	1761	3634	0.0558	24.3	43.8
Sodium	Na	11	22.997	0.97	0.035	23.7	207.5	1638	0.295	27.53	49.6
Strontium	Sr	38	87.63	2.6	0.094	33.7	1420	2523		25	45
Sulphur	S	16	32.06	2.07	0.075	15.46	235.4	832.3	0.175	9.3	16.7
Tantalum	Ta	73	180.88	16.6	0.60	10.9	5162	11,000	0.0356		
Tellurium	Te	52	127.61	6.24	0.224	20.45	846	1989	0.0468	7.305	13.15
Terbium	Tb	65	159.2				590				
Thallium	Tl	81	204.39	11.85	0.428	17.24	578	2655	0.0311	7.185	12.94
Thorium	Th	90	232.12	11.5	0.416	20.2	3353	9392	0.0276		
Thulium	Tm, Tu	69	169.4								
Tin	Sn	50	118.70	7.30	0.264	16.23	449.6	4118	0.054	14.4	25.9
Titanium	Ti	22	47.90	4.5	0.163	10.6	3272	9212	0.142		
Tungsten	W	74	183.92	19.3	0.698	9.53	6098	10,700	0.034	44	79
Uranium	U	92	238.07	18.7	0.676	12.73	3074	6332	0.0276		
Vanadium	V	23	50.95	5.68	0.205	8.97	3110	5432	0.1153		
Xenon	Xe	54	131.3	5.495x10 ⁻³	5.517x10 ⁻⁴		-169.6	-160.78			
Ytterbium	Yb	70	173.04								
Yttrium	Y	39	88.92	5.61	0.199	16.13	2700	8312			
Zinc	Zn	30	65.38	7.14	0.258	9.16	787	1665	0.09	24.09	43.36
Zirconium	Zr	40	91.22	6.4	0.23	14.3	3092	9122	0.066		

*Liquid at -62°C.

*Sublimes.

*Single crystal, 22.4 || crystal axis

46.4 ⊥ crystal axis

*Single crystal, 12.4 || crystal axis

25.8 ⊥ crystal axis

Linear Coefficient of Thermal Expansion/ $^{\circ}\text{C.}$ at Room Temperature	Linear Coefficient of Thermal Expansion/ $^{\circ}\text{F.}$ at Room Temperature	Thermal Conductivity, cal./cm. 2 /cm. $^{\circ}\text{C.}/\text{sec.}$ at Room Temperature	Electrical Resistivity, Microhm-cm.	Modulus of Elasticity (Tension), psi.	Type of Crystal Lattice	Lattice Constant ($A = 10^{-8}$ cm.) $20^{\circ}\text{C.} (68^{\circ}\text{F.})$			Closest Approach of Atoms, \AA	Elements
						a	b	c		
$\times 10^{-6}$	$\times 10^{-6}$			$\times 10^{-8}$						
29.5	16.4	0.083	20.65	2.56	Face-Centered Cubic	4.9389			3.492	Lead
56	31	0.17	8.5		Body-Centered Cubic	3.51			3.0	Lithium
										Lutecium
25.7	14.3	0.37	4.46	6.25	Hexagonal Close Packed	3.2022	5.1991		3.190	Magnesium
23	12.8				Cubic (Complex)*	8.894			1.065	Manganese
										Masurium
		0.0200	95.8							Mercury
5.49	3.05	0.350	4.77	50.2	Body-Centered Cubic	3.1403			2.720	Molybdenum
			79		Hexagonal Close Packed*	3.657	5.880		3.62	Neodymium
		1.092×10^{-4}								Neon
13.7	7.6	0.140	6.9	30	Face-Centered Cubic*	3.517			2.486	Nickel
		0.600×10^{-4}								Nitrogen
5.70	3.2		9		Hexagonal Close Packed	2.7304	4.3099		2.670	Osmium
		0.589×10^{-4}								Oxygen
11.60	6.4	0.161	10	1.70×10^7	Face-Centered Cubic	3.8817			2.744	Palladium
125	69		10^{17}							Phosphorus (Yellow)
8.8	4.3	0.166	9.83	2.14×10^7	Face-Centered Cubic	3.9158			2.768	Platinum
					Monoclinic; $\beta = 92^{\circ}$	7.42	4.29	14.10	2.81	Polonium
83	46	0.237	7.0		Body-Centered Cubic	5.333			4.62	Potassium
			88		Hexagonal Close Packed*	3.657	5.924		3.63	Praseodymium
										Protactinium
										Radium
										Radon
a	b		21		Hexagonal Close Packed	2.755	4.449	2.734		Rhenium
8.9	4.5	0.213	4.93	4.25×10^7	Face-Centered Cubic*	3.7957			2.684	Rhodium
90.0	50.0		12.5		Body-Centered Cubic	5.7			4.9	Rubidium
8.5	4.7		10		Hexagonal Close Packed*	2.698	4.274	2.644		Ruthenium
										Samarium
										Scandium
37.0	20.6		12		Hexagonal*	4.337	4.944	2.32		Selenium
	1.6-4.1	0.20	85×10^3	16	Cubic (Diamond)	5.4173			2.346	Silicon
18.9	10.5	0.974	1.62	10.3	Face-Centered Cubic	4.0774			2.882	Silver
71	39.5	0.3225	4.6		Body-Centered Cubic	4.30			3.72	Sodium
			22.76		Face-Centered Cubic*	6.075			4.30	Strontium
67.48	37.49	0.00063	1.9×10^{17}		Face-Centered Orthorhombic*	10.48	12.92	24.55	2.12	Sulphur
6.5	3.6	0.130	15.5	27.0	Body-Centered Cubic	3.2959			2.854	Tantalum
16.8	9.3	0.01433			Hexagonal	4.445	5.912		2.86	Tellurium
										Terbium
28.0	15.6	0.09315	18.1		Hexagonal Close Packed*	3.450	5.520		3.40	Thallium
12.3	6.84		18		Face-Centered Cubic*	5.077			3.59	Thorium
										Thulium
e	k	0.157	11.5	5.9-7.8	Body-Centered Tetragonal*	5.819	3.175	3.016		Tin
7.14	3.96				Hexagonal Close Packed*	2.953	4.729	2.90		Titanium
4.0	2.2	0.476	5.48	60	Body-Centered Cubic*	3.1585			2.734	Tungsten
			60		Orthorhombic*	2.852	5.865	4.945	2.76	Uranium
			26		Body-Centered Cubic	3.033			2.627	Vanadium
		1.24×10^{-4}								Xenon
										Ytterbium
					Hexagonal	3.663	5.814	3.59		Yttrium
f	g	0.268	h		Hexagonal Close Packed	2.659	4.936	2.658		Zinc
6.3	3.5		41		Hexagonal Close Packed*	3.223	5.123	3.16		Zirconium

* $20-1917^{\circ}\text{C.}$, 12.5 || crystal axis
 4.7 || crystal axis
 * $20-1917^{\circ}\text{C.}$, 6.94 || crystal axis
 2.61 || crystal axis
 *Ordinary form at 20°C. ; other modifications known or probable at other temperatures.

*32.5 pure, hot rolled zinc with grain
 25.0 " " " across rolling
 *18.0 pure, hot rolled zinc with grain
 12.8 " " " across rolling
 *Single crystal, 6.2 || crystal axis
 5.8 || crystal axis

Density of Alloys*

(at 60°F.)

Material or Trade Designation	Approx Composition, %	Cast		Wrought	
		sp gr.	lb./in. ³	sp.gr.	lb./in. ³
Aluminum and Aluminum Alloys					
Aluminum	Al 99 97	.....	.....	2.70	0 0975
12 and 212, ASTM-B, SAE-30.....	Cu 8	2.82	0.102	.....	.....
43, ASTM-J, SAE-35.....	Si 5	2.66	0.096	.....	.....
47, ASTM-K, SAE-37.....	Si 12.5	2.63	0.095	.....	.....
108	Cu 4, Si 3	2.74	0.099	.....	.....
109, ASTM-E, SAE-32.....	Cu 12	2.91	0.105	.....	.....
112, ASTM-C, SAE-33.....	Cu 7, Zn 2, Fe 1 2	2.85	0.103	.....	.....
122T2 } 122T61 } ASTM-F, SAE-34..	Cu 10, Fe 1 2, Mg 0 2	2 93	0 106	.....	.....
142, ASTM-H, SAE-39.....	Cu 4, Ni 2, Mg 1 5	2 80	0 101	.....	.....
195, ASTM-G, SAE-38.....	Cu 4 5	2 77	0.100	.....	.....
214	Mg 3 7	2.63	0.095	.....	.....
216	Mg 6	2.60	0.094	.....	.....
220	Mg 10	2.55	0.092	.....	.....
A 334.....	Cu 3, Si 4, Mg 0 3	2.74	0.099	.....	.....
355.....	Cu 2, Si 5, Mg 0.5	2.69	0.097	.....	.....
A 355.....	Cu 1.4, Si 5, Mn 0.7, Ni 0.7, Mg 0.5	2.74	0.099	.....	.....
356.....	Si 7, Mg 0 3	2 63	0.095	.....	.....
645.....	Zn 11, Cu 2 5, Fe 1 5	2 93	0.106	.....	.....
A 108	Cu 4 5, Si 5 5	2 74	0.099	.....	.....
B 113.....	Cu 7, Si 1 5, Fe 1 2	2 88	0.104	.....	.....
132.....	Si 14, Cu 1, Fe 1, Mg 1, Ni 2	2.71	0.098	.....	.....
144.....	Cu 10, Si 4, Mg 0 25	2 88	0.104	.....	.....
B 195.....	Cu 4.5, Si 3	2 77	0.100	.....	.....
D 195.....	Cu 5 5	2.82	0.102	.....	.....
A 214.....	Mg 3 75, Zn 2	2.66	0.096	.....	.....
2S	Commercial Al	.....	.....	2 71	0 098
3S	Mn 1 25	.....	.....	2.73	0 099
4S	Mn 1 25, Mg 1	.....	.....	2 72	0 098
17S (Duralumin)	Cu 4, Mn 0 5, Mg 0 5	.....	.....	2.79	0 101
24S	Cu 4 2, Mn 0 6, Mg 1 5	.....	.....	2 76	0 100
25S	Cu 4 5, Si 0 8, Mn 0 8	.....	.....	2.79	0.101
51S	Si 1, Mg 0.6	.....	.....	2 69	0 097
52S	Mg 2 5, Cr 0 25	.....	.....	2 67	0.096
53S	Si 0 7, Mg 1 25, Cr 0 25	.....	.....	2 69	0 097
Copper and Copper Alloys					
Copper (electrolytic)	99 90 +	.....	.....	8 89	0 3217
(deoxidized)	99 90 +	.....	.....	8 93	0 323
Primer Gilding	Cu 97, Zn 3	.....	.....	8 89	0 321
Gilding	Cu 95, Zn 5	.....	.....	8 866	0 320
Commercial Bronze	Cu 90, Zn 10	.....	.....	8 804	0 318
Red Brass 85%	Cu 85, Zn 15	.....	.....	8 745	0 316
Red Brass 80%	Cu 80, Zn 20	.....	.....	8 667	0 313
Brazing Brass	Cu 75, Zn 25	.....	.....	8 594	0 310
Spring Brass	Cu 72, Zn 28	.....	.....	8 553	0 309
Cartridge Brass	Cu 70, Zn 30	.....	.....	8 528	0 308
Eyelet Brass	Cu 68, Zn 32	.....	.....	8 50	0 307
Commercial High Brass.....	Cu 65, Zn 35	.....	.....	8 47	0 306
Brass Wire	Cu 63, Zn 37	.....	.....	8 437	0 305
Muntz Metal	Cu 60, Zn 40	.....	.....	8 396	0 303
Tube Brass	Cu 67.5, Zn 32, Pb 0 5	.....	.....	8 495	0 307
Leaded Comm. Bronze.....	Cu 88 5, Zn 10, Pb 1 5	.....	.....	8 83	0 319
Leaded Red Brass 80%.....	Cu 78.5, Zn 20, Pb 1 5	.....	.....	8 698	0 314
Leaded Brass	Cu 69, Zn 29 5, Pb 1 5	.....	.....	8 562	0 309
Forging Brass	Cu 60, Zn 38, Pb 2	.....	.....	8 44	0 305
Free Cutting Rod.....	Cu 62, Zn 35, Pb 3	.....	.....	8 489	0 307
Naval Brass or Tobin Bronze.....	Cu 60, Zn 39 25, Sn 0 75	.....	.....	8 404	0 304
Fourdrinier Wire	Cu 81, Zn 18 75, Sn 0 25	.....	.....	8 712	0 315
Special Bronze	Cu 98.75, Sn 1 25	.....	.....	8 89	0 321
Signal Bronze	Cu 98 25, Sn 1.75	.....	.....	8 89	0 321
Phosphor Bronze	Cu 96, Sn 3 75, P 0 25	.....	.....	8 88	0 320
Chain Bronze	Cu 95, Sn 5	.....	.....	8 87	0 320
Leaded Chain Bronze.....	Cu 94, Pb 1, Sn 5	.....	.....	8 929	0 322
Gun Metal	Cu 92, Sn 8	.....	.....	8 815	0 318
Coe Bronze	Cu 89 5, Sn 10 5	.....	.....	8 78	0 317
Free Cutting Phos. Bronze....	Cu 88, Zn 4 Pb 4, Sn 4	.....	.....	8 86	0 320
Super Nickel	Cu 70, Ni 30	.....	.....	8 95	0 323
15% Cupro Nickel.....	Cu 85, Ni 15	.....	.....	8 95	0 323
Constantan	Cu 55, Ni 45	.....	.....	8 90	0 322

(Continued)

*Compiled by the Subcommittee on Physical Constants. The membership of the subcommittee was as follows: R. L. Kenyon, Chairman, H. W. Russell, J. B. Johnson, C. S. Barrett

Material or Trade Designation	Approx. Composition, %	Cast		Wrought	
		sp.gr	lb./in. ³	sp.gr.	lb./in. ³
30% Nickel Silver.....	Cu 47, Zn 23, Ni 30	.....	.....	8.74	0.316
Ambrac B	Cu 65, Zn 5, Ni 30	.....	.....	8.86	0.320
Ambrac A	Cu 75, Zn 5, Ni 20	.....	.....	8.86	0.320
25% Nickel Silver.....	Cu 55, Zn 20, Ni 25	.....	.....	8.72	0.315
18% Nickel Silver.....	Cu 65, Zn 17, Ni 18	.....	.....	8.752	0.316
18% Nickel Silver.....	Cu 55, Zn 27, Ni 18	.....	.....	8.68	0.314
15% Nickel Silver.....	Cu 64, Zn 21, Ni 15	.....	.....	8.691	0.314
15% Nickel Silver.....	Cu 57, Zn 28, Ni 15	.....	.....	8.631	0.312
10% Nickel Silver.....	Cu 65, Zn 25, Ni 10	.....	.....	8.675	0.313
5% Aluminum Bronze.....	Cu 95, Al 5	.....	.....	8.176	0.295
8% Aluminum Bronze.....	Cu 92, Al 8	.....	.....	7.80	0.281
8% Al Bronze with Fe.....	Cu 89.5, Al 8, Fe 2.5	.....	.....	7.74	0.280
10% Al Bronze.....	Cu 90, Al 10	.....	.....	7.57	0.273
Avialite	Cu 90, Al 9.50, Fe 0.5	.....	.....	7.585	0.274
Calson Bronze.....	Cu 95.5, Al 2.5, Sn 2.0	.....	.....	8.540	0.308
Manganese Bronze.....	Cu 89, Zn 39, Mn 0.5, Fe 0.80, Sn 0.70	.....	.....	8.370	0.302
Everdur 1010	Cu 96, Mn 1, Si 3	.....	.....	8.539	0.308
Everdur 1015	Cu 98.25, Mn 0.25, Si 1.5	.....	.....	8.740	0.316
Hitenso A	Cu 99.35, Cd 0.65	.....	.....	8.89	0.321
Hitenso BB	Cu 99, Cd 1	.....	.....	8.89	0.321
Hitenso C	Cu 98.6, Cd 0.8, Sn 0.6	.....	.....	8.89	0.321
Tempaloy 917	Cu 81.9, Fe 2.5, Ni 5, Al 9.6, Mn 1	.....	.....	7.569	0.273
Architectural Bronze.....	Cu 57, Zn 40, Pb 2.5, Sn 0.34, Fe 0.16	.....	.....	8.432	0.305
Beryllium Copper.....	Cu 97.75, Be 2.25	.....	.....	8.23	0.297
Bronze A	Cu 87, Al 9.8, Fe 3.2	.....	.....	7.71	0.279
Bronze B	Cu 85.8, Al 10.8, Fe 3.6	.....	.....	7.58	0.274
Die Casting Alloys					
ASTM-XXI, SAE-921	Zn 92.8, Cu 3, Al 4, Mg 0.1, Fe 0.1	6.7	0.242	...	..
ASTM-XXIII, SAE-903	Zn 95.75, Cu 0.1, Al 4, Mg 0.05, Fe 0.1	6.64	0.240	..	..
Bearing Metals					
ASTM-1	Cu 4.5, Sn 91, Sb 4.5	7.34	0.265	.....	.....
ASTM-2	Cu 3.5, Sn 89, Sb 7.5	7.39	0.267	.....	.....
ASTM-3	Cu 8 $\frac{1}{4}$, Sn 83 $\frac{1}{4}$, Sb 8 $\frac{1}{4}$	7.46	0.269	.....	.....
ASTM-4	Cu 3, Sn 75, Sb 12, Pb 10	7.52	0.272	.....	.....
ASTM-5	Cu 2, Sn 65, Sb 15, Pb 18	7.50	0.280	.....	.....
ASTM-6	Cu 1.5, Sn 20, Sb 15, Pb 63.5	9.33	0.337	.....	.....
ASTM-7	Sn 10, Sb 15, Pb 75	9.73	0.352	.....	.....
ASTM-8	Sn 5, Sb 15, Pb 80	10.04	0.363	.....	.....
ASTM-9	Sn 5, Sb 10, Pb 85	10.24	0.370	.....	.....
ASTM-10	Sn 2, Sb 15, Pb 83	10.07	0.364	.....	.....
ASTM-11	Sb 15, Pb 85	10.28	0.371	.....	.....
ASTM-12	Sb 10, Pb 90	10.67	0.386	.....	.....
SAE 65 (T-1).....	Cu 88.75, Sn 11, Pb 0.25	8.5	0.307	.....	.....
SAE 63 (T-2).....	Cu 87.5, Sn 11, Pb 1.5	8.8	0.316	.....	.....
T-3.....	Cu 85, Sn 10, Pb 5	8.7	0.314	.....	.....
T-4.....	Cu 84, Sn 10, Pb 2.5, Ni 3.5	8.8	0.318	.....	.....
T-5.....	Cu 84, Sn 16	8.6	0.310	.....	.....
T-6.....	Cu 80, Sn 20	8.7	0.314	.....	.....
T-7.....	Cu 80, Sn 10, Pb 10	8.9	0.322	.....	.....
T-8.....	Cu 78, Sn 8, Pb 14	9.4	0.339	.....	.....
T-9.....	Cu 70, Sn 9, Pb 21	9.5	0.346	.....	.....
T-10.....	Cu 70, Sn 4, Pb 26	9.7	0.376	.....	.....
T-11.....	Cu 10, Al 4, Zn 86	6.9	0.250	.....	.....
Illium	Ni Cr Cu	.....	.....	8.3	0.3
Ferrous Metals					
Iron	99.97 Fe	.....	.....	7.87	0.284
Armco Iron	<0.1 Total of C, Mn, S, P, S	.....	.....	7.86	0.284
Soft Steel	C 0.10	.....	.....	7.85	0.284
Structural Steel	C 0.25	.....	.....	7.85	0.284
Carbon Steel	C 0.40	.....	.....	7.84	0.283
Spring Steel	C 0.75	.....	.....	7.83	0.283
Tool Steel	C 0.90	.....	.....	7.82	0.283
Malleable Cast Iron.....	C 2.50	7.42	0.268	.....	.....
Gray Cast Iron.....	C 3.50	7.0-7.22	0.253-0.261	.....	.....
Strong Gray Cast Iron.....	C 3.50	7.22	0.261	.....	.....
High Strength Cast Iron.....	C 3.00	7.30	0.264	.....	.....
Alloy Cast Iron.....	C 2.75	7.35	0.266	.....	.....
Wrought Iron .....		.....	.....	7.4-7.9	0.267-0.285

(Continued)

Material or Trade Designation	Approx. Composition, %	Cast		Wrought	
		sp.gr.	lb./in. ³	sp.gr.	lb./in. ³
Stainless Steel	Cr 18-20, Ni 8-10,	....	....	7.92	0.286
Stainless Steel	Cr 22-26, Ni 11-13, C 0.20	....	....	7.84	0.283
Stainless Steel	Cr 16-18, C 0.12	....	....	7.86	0.273
Stainless Steel	Cr 23-30, C 0.35	....	....	7.48	0.270
Duriron	Si 14.5, Mn 0.35, C 0.80, Fe Bal.	7.0	0.253	....	....
Silicon Steel (Magnetic)	Si 0.60	....	....	7.5	0.271
Silicon Steel (Magnetic)	Si 1.00	....	....	7.5	0.271
Silicon Steel (Magnetic)	Si 1.17	....	....	7.7	0.278
Silicon Steel (Magnetic)	Si 1.30	....	....	7.7	0.278
Magnesium Alloys					
Magnesium .....	.....	....	....	1.74	0.063
ASTM-1 Dow-A	Al 8, Mn 0.2, Mg 91.8	1.80	0.065	....	....
ASTM-2 Dow-G	Al 10, Mn 0.1, Mg 89.9	1.81	0.068	....	....
ASTM-3 Dow-B	Al 12, Mn 0.1, Mg 87.9	1.82	0.068	....	....
ASTM-4 Dow-H	Al 6, Mn 0.2, Zn 3, Mg 90.8	1.84	0.068	....	....
ASTM-6 Dow-F	Al 4, Mn 0.3, Mg 95.7	....	....	1.77	0.064
ASTM-8 Dow-J	Al 6.5, Mn 0.3, Zn 0.75, Mg 92.45	....	....	1.81	0.065
ASTM-9	Al 8.5, Mn 0.2, Zn 0.5, Mg 90.8	....	....	1.83	0.066
ASTM-10	Mn 1.0, Sn 6.0, Mg 93	....	....	1.85	0.067
ASTM-11 Dow-M	Mn 1.5, Mg 98.5	....	....	1.76	0.064
ASTM-14	Al 10, Mn 0.1, Zn 1.0, Mg 88.9	1.82	0.06575	....	....
Nickel and Nickel Alloys					
Nickel .....	.....	....	....	8.85	0.320
Copper-Nickel	Ni 20, Cu 80	....	....	8.98	0.324
Copper-Nickel	Ni 30, Cu 70	....	....	8.93	0.323
Copper-Nickel	Ni 45, Cu 55	....	....	8.90	0.322
Copper-Nickel	Ni 70, Cu 30	....	....	8.80	0.318
Monel	Ni 65-70, Cu 26-30, Fe 3, Mn 1.5, Si 0.25, C 0.25	....	....	8.80	0.318
Permalloy	Ni 78	....	....	8.6	0.311
Hypernik	Ni 50	....	....	8.3	0.300

Heat Contents Above 0°C.*

	°C. 100	200	300	400	600	800	1000	1200	1500
	°F. 212	392	572	752	1112	1472	1832	2192	2732
Calories Per Gram†									
Aluminum	21.2	43.8	67.9	93.8	148S	296L	348	...	...
Antimony	5.0	10.1	15.4	20.9	32.3S	83.2L	95	...	...
Arsenic	8.0	16.3	24.8	33.5	52.2	73.6	...	...	...
Beryllium	43.8	94.8	152	212	339	474	...	...	...
Bismuth	2.98	6.07S	21.4L	25.1	32.3	39.6	46.8	...	...
Boron	25.2	56.7	94.4	136.8	230	333	...	...	...
Cadmium	5.6	11.3	17.4S	36.6L	49.3	62	...	...	...
Calcium	15.9	32.2	50.3	68.9a	108.5	149	...	...	...
				71.7β					
Carbon	20.7	45.4	74.3	108.2	183.5	269	357	448	590
Chromium	11.1	23	35.1	47.6	73.8	103	135	170	229
Cobalt	10.5	21.6	33.1	45.5	71.6	99.5	131	163.5S	279L
Copper	9.3	18.8	28.7	38.6	59.3	81	103S	175.5L	211
Germanium	7.4	15.1	23.1	30	...	...	...	...	...
Gold	3.05	6.2	9.4	12.75	19.7	26.7	34S	56.8L	67.4
Iron	10.9	22.7	36	50.7	83.6a	126β	165.5γ	196γ	247
Iridium	3.1	6.3	9.55	12.8	19.8	26.9	34.5	42.2	54.5
Lead	3.1	6.3	9.6S	18.8L	25.4	32	38.6	...	...
Lithium	91	...	...	...	...	...	...	...	...
Magnesium	24.6	50.6	77.8	106	165S	267L	...	...	...
Manganese	11.2	23.7	37.3	52.8	87.8	128a	166β	207γ	330L
Molybdenum	6.05	12.5	19.3	26.3	41	56.5	72.5	89.9	117
Nickel	10.9	22.7	35.7a	50.7β	77	103.8	131	159β	274L
Osmium	3.1	6.3	9.5	12.8	19.5	26.3	33.5	40.7	...
Palladium	5.6	11.3	17.2	23.7	36.6	50.4	64.5	79.5	102.8
Platinum	3.2	6.5	9.8	13.1	20.2	27.4	34.9	42.7	54.6
Rubidium	6.0	12.1	18.4	24.9	38.9	53.7	69.1	85.2	110.5
Ruthenium	6.7	13.6	20.6	27.8	42.8	58.7	75.3a	92.6βγ	119β
Selenium	7.9	16.7S	33.5L	...	...	...	...	...	...
Silicon	17.6	36.6	57.2	78.0	121	165	...	...	...
Silver	5.6	11.3	17.2	23.3	35.9	49S	86L	103	...
Tantalum	3.4	6.9	10.5	14.1	21.5	29.1	...	...	...
Tellurium	4.7	9.6	14.8	20.0	...	...	...	...	...
Thallium	3.2	6.6a	11.0β	18.2L	25.1	...	...	...	...
Tin	5.6	11.6S	31.8L	37.4	48.5	59.7	70.8	...	...
Titanium	11.3	25.3	44.5	63.7	...	...	...	...	...
Tungsten	3.3	6.5	9.9	13.2	20.1	27.1	34.4	41.8	53.5
Zinc	9.4	19.1	29.4	40.0S	88.5L	114	...	...	...

S = Solid. L = Liquid.

†Multiply by 1.8 to convert to B.t.u. per lb.

*Selected from Bureau of Mines Bulletin No. 371, by the Subcommittee on Physical Constants. The membership of the subcommittee was as follows: R. L. Kenyon, Chairman, H. W. Russell, J. B. Johnson, and C. S. Barrett.

Properties of Metals at Low Temperatures

By R. K. Hopkins* and H. S. Blumberg†

General—Large sized pressure vessels are used mainly in the petroleum and chemical industries. In the former, most common application is in the oil dewaxing process where propane or some other suitable liquid is used as a refrigerant at temperatures in the range -40 to -75°F. and at high pressures. In the chemical industry a number of heavy walled pressure vessels are operating at temperatures as low as -150°F. Operating temperatures as low as that of liquid air have also been reported.

Because of the danger incident to the use of low vapor pressure liquids such as propane, the utmost care should be exercised in selecting materials for this service. Attention should be given to composition, melting history, mill processing, methods of fabrication, and heat treatment.

Definition of "Low Temperatures"—The definition of the term "low temperatures" is of necessity arbitrary. It is felt that the range of temperatures included should be as wide as possible, particularly since many metals are quite sensitive to slight lowering of temperature below room temperature, and in some cases even at temperatures somewhat above atmospheric. Accordingly, "low temperatures" as used in this article will refer to all temperatures below room temperature. Wherever the term is used specifically, a definite temperature range should be mentioned.

Importance and Relation of Welding—A great many large parts used at low temperatures are fabricated by welding. Welded joints are usually considered to consist of three zones which merge into each other, namely, base metal, weld metal proper, and the heat affected zone between the two. Therefore, the properties of a welded joint at low, as well as room, temperature should be considered with reference to these three zones.

Where welding is part of fabrication procedure, tests should be carried out to insure weld quality, particularly with reference to impact resistance. Test bars should be notched at various locations in the welded joint, through the weld proper, junction of weld and heat affected zone, the center of the heat affected zone, junction of heat affected zone and base metal, and the base metal proper.

It is important that, wherever possible, laboratory tests be augmented by tests on large models having the same symmetry as a full sized vessel. Such tests are extremely valuable, particularly when a new material is being used for the first time.

Forms Used for Low Temperature Service—Pressure vessels and other large parts are usually made from large rolled plates. Smaller parts are made from wrought material and in many cases castings are satisfactorily used.

In the majority of cases, operating temperatures do not fall below -150°F. Properly made low carbon steel is satisfactory down to -100°F. and certain low alloy steels give good impact values down to -150°F. Where operating temperatures are below -150°F. , special materials such as austenitic stainless steels and certain nonferrous metals should be used.

Wrought materials in rolled form are usually used for pressure vessels. The directional properties must be considered, as it is usual to find that transverse bars are lower than longitudinal ones in ductility and shock resistant properties as determined by laboratory tests. Segregation is also an important factor and thus, where large plates are fabricated, tests should be made from representative parts of the plate. Because of the extreme dimensions of large plates, it is practical to heat treat only by annealing or normalizing. Thus a number of compositions which would meet notched bar shock test requirements in the quenched and tempered condition are not used in heavy sections which do not lend themselves to drastic heat treatments.

Where castings can be used, such as in smaller parts, the fabricator has at his command many more compositions than are available for large heavy plates. In general it may be said that for castings there can be used all those materials satisfactory for heavy plates. However, the castings should generally be quenched and tempered, although in a number of compositions simple heat treatment will suffice.

*Director of Metallurgical Research and Development, and †Chief Metallurgist, M. W. Kellogg Co., Jersey City, N. J.

Properties of Metals at Low Temperatures—The lowering of the temperature of metals below room temperature is generally accompanied by an increase in the tensile strength and yield point and a lesser decrease in elongation and reduction of area as measured in a tension test bar. The property which is affected most by lowering temperature is the resistance to shock.

Tension Test Properties—There is a large amount of data available on tension test results on various compositions at low temperatures. Selected results are given in Tables I-III, covering carbon steels, alloy steels, cast irons, and nonferrous alloys.

Impact Properties—Interpretation of impact data on a quantitative basis with relation to use in design and in service is extremely difficult for a number of reasons. The phenomenon of the shock resistance of steels is extremely complex and does not lend itself to simple analysis. The fundamentals of impact testing are still far from being understood and, more important, therefore, is the fact that no quantitative use of impact tests is made in design. The range of such service factors as notch effect, velocity of blow, energy of blow, or combination with other stresses, are difficult to vary sufficiently in the laboratory to evaluate properly.

Rational use of data is based on experience, in that service history of metals of known impact properties dictates acceptable or unacceptable material. It is generally accepted that a Charpy ft-lb. value is satisfactory upon the basis of 10 ft-lb. minimum for subzero service.

When impact tests on ductile materials are carried out, an unnotched specimen

Table I
Tensile Results on Steels at Low Temperatures

Authority	Material	Treatment, °F.	Test Temp., °F.	Tensile Strength, psi	Yield Point, psi.	Elong., % in 2 in.	Red. Area, %	Brinell
<i>Carbon Steels</i>								
Colbeck MacGillivray Manning	Armco C 0.035%	As rec'd.	Room	45,700	....	27.9	73.2	
			— 4	53,750	30,700	42.0	75.0	
			— 58	59,400	42,200	43.0	74.0	
			— 94	61,700	43,400	37.5	72.0	
			—148	66,800	57,200	26.5	70.0	
			—184	77,000	66,700	17.0	68.0	
Hadfield	Swedish charcoal iron C 0.03%, Mn 0.04%	As forged	Room	52,500	41,700	25	81.0	104
			—296	116,500	....	Nil	...	230
			—423	117,000	117,000	Nil	Nil	232
Colbeck etc	C 0.13%	As rec'd.	Room	66,300	54,700	29.7	71.8	
			— 85	80,700	67,700	33.8	70.3	
			—292	121,300	....	26.5	55.0	
Hadfield	Carbon steel C 0.14%, Mn 0.07%	Annealed 1472	Room	45,700	42,700	27.5	77.5	114
			—296	137,000	....	7.5	...	281
			—423	155,000	155,000	0.3	2.5	326
Sands	C 0.21%	As rec'd	Room	62,600	39,800	35.5	53.0	
			—114	69,000	47,780	35.5	56.8	
Bull	Rolled bar C 0.21%, Mn 0.60%		Room	62,600	39,800	35.5	53.0	
			—114	68,995	47,780	35.5	56.8	
Bull	Carbon casting C 0.21%, Mn 0.70%		Room	71,840	32,195	34.8	55.3	
			—114	77,585	39,540	33.3	52.5	
Bull	Carbon forging C 0.26%, Mn 0.46%		Room	57,300	38,940	34.0	54.7	
			—114	72,840	50,325	36.0	53.2	
Kinzel Crafts Egan	S.A.E. 1038	Normalized	+ 25	85,000	50,000	29.0	52.0	
			— 25	95,000	60,000	27.0	48.0	
			— 60	102,000	76,000	30.0	48.0	
			—190	144,000	143,000	5.0	5.0	
Hadfield	Carbon steel C 0.37%, Mn 0.29%	Annealed 1472	Room	76,200	....	20.0	63.0	157
			—296	148,000	....	17.0	39.0	294
			—423	151,000	151,000	Nil	Nil	316
Strauss	C 0.40%	Annealed	Room	79,400	45,600	30.8	49.0	
			Liq. air	139,400	114,100	7.3	7.1	
Strauss	C 0.40%	Treated	Room	104,400	76,900	25.0	61.3	
			Liq. air	160,400	150,200	9.8	9.4	
Bull	Carbon forging C 0.40%, Mn 0.52%		Room	77,440	44,670	29.0	45.3	
			—114	83,310	47,075	30.8	44.9	
Hadfield	Carbon steel C 0.78%, Mn 0.10%	Annealed 1472	Room	99,000	95,000	12.0	35.0	194
			—296	154,700	....	Nil	...	325
			—423	123,000	123,000	0.2	Nil	244

Table I—Continued
Tensile Results on Steels at Low Temperatures

Authority	Material	Treatment, °F.	Test Temp., °F.	Tensile Strength, psi.	Yield Point, psi.	Elong., % in 2 in.	Red. Area, %
<i>Alloy Steels</i>							
Hurtgen	C 0.53%	1500 oil	+100	135,000	90,000	21.0	62
	Cr 0.97%	1120 tempered	0	138,000	97,500	21.5	59
	Mo 0.22%		-100	150,000	107,500	22.0	55
Colbeck etc.	C 0.33%		Room	152,000	137,700	14.0	65.0
	Cr 0.67%	1560 oil	- 6	154,500	141,000	15.6	64.0
	Ni 2.45%	1185 tempered	- 76	164,000	143,300	14.0	63.0
	Mo 0.64%		- 90	163,000	145,500	15.6	62.0
			-141	170,000	149,000	16.4	61.0
			-292	201,500	183,500	17.0	63.0
Hadfield	C 0.35%	Oil quench,	Room	146,000	133,000	13.5	59.5
	Cr 0.71%	1200 tempered	-423	243,000	243,000	4.5	48.5
Strauss	Ni 3%	Annealed	Room	79,400	57,000	31.5	57.2
			Liq. air	116,800	111,000	6.8	6.7
		Treated	Room	98,800	76,400	27.3	65.9
			Liq. air	148,700	132,900	15.5	17.6
Strauss	Cr 14%	Treated	Room	225,800	212,200	9.8	37.3
			Liq. air	259,700	210,800	2.8	3.5
Strauss	Cr 16%	Annealed	Room	75,100	42,800	34.0	70.8
			Liq. air	145,700	123,200	14.0	14.3
Strauss	Cr 20%	Treated	Room	91,900	51,900	24.0	59.3
			Liq. air	99,200	99,200	0.0	0.0
Nickel Steel Topics	C 1.27%		Room	148,000	77,300	44.5	39.0
	Mn 12.69%		-296	137,000	.....	2.5	...
			-423	146,000	146,000	Nil	Nil
Hadfield	Cr 18%		Room	117,000	.....	56.0	54.0
	Ni 8%		-423	268,000	.....	25.0	31.0
Russell	Cr 8%	Annealed	Room	107,600	48,300	44.3	60.1
	Ni 21%		Liq. air	180,200	102,800	25.3	21.5
Colbeck etc.	C 0.11%	Water quenched 2010	-292	232,000	77,000	30.5	45.0
Colbeck etc.	C 0.06%, Cr 13.45%	As above	Room	80,400	38,500	59.5	75.5
	Ni 10.05%, Mn 4.07%		-292	197,500	89,500	47.0	60.0
Hadfield	C 0.41%		Liq. air	353,000	.....	15.0	...
	Ni 20.0%						
Nickel Steel Topics	C 0.56%		Room	120,500	.....	20.4	...
	Ni 24.6%		-112	160,000	.....	14.1	...
Russell	Ni 26%	Annealed	Room	99,800	52,900	38.3	52.1
			Liq. air	205,000	157,800	11.5	9.7
Russell	C 0.56%		64	120,500	71,200	20.4	67.4
	Ni 24.6%		-112	160,000	105,000	14.1	64.0
	Mn 1.18%						

will usually bend as in a slow bend test with no failure. This takes place even at extremely low temperatures in most materials which fail with low absorbed energy values in notched sections. Accordingly, unnotched bars are of little value in determining differences between various materials. In design and manufacture notched and sudden changes in section should be avoided.

The Charpy and Izod impact tests are most commonly used. Details of these tests will be found in another article in this Handbook. The Izod test is extremely sensitive to changes in notch and results are somewhat more erratic than in the Charpy test when the keyhole notch is used in the latter. There is a constantly growing tendency, therefore, for specifications to contain requirements upon Charpy keyhole impact specimens. In the earlier literature, Fremont impact tests were reported, but this machine is only infrequently used today.

A recent impact test which appears unusually promising is the tensile impact test. It is expected that this test will come into more prominent use, because it is possible to obtain information as to the effect of velocity of the blow to a much greater degree than in the other impact tests.

It should be mentioned that all impact tests made today give "single blow" data. There appears to be no data on repeated impact tests at low temperatures.

Carbon Steels—Herty and co-workers¹ have made a thorough study of the effect of deoxidation on the impact strength of carbon steels at low temperatures. Compo-

sitions studied varied from 0.14-0.48% carbon. Correctly deoxidized steels with 0.22% carbon and less had satisfactory low temperature values down to -40°F. , while 0.48% carbon steel showed low results at -2°F. even though correctly treated. Herty points out the harmful effect of overheating in heat treatment and the decided lowering of the impact values if the steels are not properly normalized.

The low temperature Charpy impact properties of carbon steels are related to composition, melting history, heat treatment, and microstructure. Thus, when low carbon steels are made without being properly deoxidized, the authors¹¹ have shown that impact properties drop off suddenly in the vicinity of 0°F. , whereas when these steels are properly treated in the melting process, good values are obtained down to -100°F. All of these steels were found to be readily weldable, and the test values easily passing the Boiler Code requirements for pressure vessels. Table IV gives the average results of three impact tests of each of sixteen normalized and stress relieved carbon steels made with varying deoxidation practice. Impact values of weld metal are also given. It will be noted that the silicon and aluminum killed heats maintained acceptable impact values down to -100°F. , while one of the heats deoxidized with silicon alone gave poor or erratic values at 0°F.

Table II
Tensile Results on Cast Iron at Low Temperatures*

Material	Composition	Test Temp., $^{\circ}\text{F.}$	Tensile Strength, psi.
Machine cast iron medium strength	C 3.56% Graphite 3.08% Si 1.80%	75	20,500
		-4	22,000
		-112	
		-150	
High grade machine cast iron	C 3.42% Graphite 2.35% Si 1.24%	75	31,000
		-4	30,000
		-112	
		-150	
Pipe cast iron	C 3.64% Graphite 2.94% Si 1.81%	75	22,000
		-4	22,500
		-112	24,000
		-150	24,700
Hematite cast iron	C 3.78% Graphite 3.26% Si 2.03%	75	18,000
		-4	19,000
		-112	
		-150	21,000
Iron for thin walled castings	C 3.42% Graphite 2.82% Si 2.17%	75	22,000
		-4	22,200
		-112	24,000
		-150	24,600

*H. W. Russell.

As pointed out by Sands,⁴ carbon content of carbon steels is a factor. Aluminum killing is effective only when the carbon content does not exceed 0.30%. Above this percentage, carbon exerts a harmful effect even when steels are aluminum killed.

Kinzel and co-workers⁵ conclude that "aluminum killed, normalized, plain carbon steels of otherwise appropriate analysis, in small sections, are satisfactory for engineering service at temperatures down to -112°F. " They further state that, "welds produced with carbon steel electrodes having a combustible or mineral coating show sufficient energy absorption on low temperature notched bar impact testing to indicate their fitness for engineering service at temperatures down to -112°F. "

It is apparent, then, that properly deoxidized low carbon steel is satisfactory for service down to -100°F. These steels represent metals of lowest cost for low temperature service. They are easily weldable and weld properties are satisfactory.

Nickel Steels—The 2¼% nickel and 3½% nickel steels have shown excellent low temperature impact properties. Sands⁴ gives the following values for normalized steels of 0.20% carbon content:

Nickel, %	Brinell at room temp.	Charpy Impact Resistance, ft.-lb. Room Temp. -50°F.	
0	127	80	7
1	146	94	30
2	155	88	35
3	168	88	40
4	187	75	50

The effect of carbon in conjunction with nickel in normalized steels is pointed out in the following:

Nickel, %	Carbon, %	Charpy, ft.-lb.	
		Room Temp.	-50°F.
0	0.33	25	5
1	0.22	85	20
2	0.16	95	43
3	0.12	110	70
4	0.04	172	170

The authors⁴ describe the fabrication of a full sized 2¼% nickel steel pressure vessel, including two types of welding, heat treatment, and testing. Pressure vessels are ordinarily given a final heat treatment, as a unit, consisting of stress relieving at 1100-1200°F. followed by furnace cooling. Base metal and welded joints were shown to have acceptable properties at -75°F. and to easily pass Boiler Code requirements. Deposited weld metal of 2¼% nickel steel composition gave better values than ½% nickel welds at -50°F. Poor impact values resulting from too high a normalizing temperature were found. Microscopic studies pointed to the beneficial effect of small pearlite-ferrite grain size on base metal notched bar values.

Moses' reports on the excellent values obtained in the weld and base metal of 0.20% carbon, 3% nickel steels for pressure vessels. High values are shown at -100°F.

The results of a great deal of test data on low nickel steels are furnished in Properties of Nickel Alloy Steels at Low Temperatures.⁵ Important conclusions noted are: 1. Nickel steels of the pearlitic type containing 2-5% nickel remain quite tough at temperatures down to at least -100°F. 2. Nickel is equally as beneficial in pearlitic steel weld deposits as in rolled steel. 3. Normalizing pearlitic nickel steels at temperatures somewhat over the critical range gives values which are satisfactory for service down to -100°F. 4. Quenching and high tempering of low carbon, low and medium nickel steels have given good notched bar values at extremely low temperatures. 5. Improvements comparable to those effected in wrought steels are conferred by nickel upon cast steels as well. Cast steels should be heat treated by double normalizing and tempering.

An excellent comprehensive study of 2¼% nickel steels with special consideration for the fabrication of a dewaxing plant to operate at temperatures as low as -75°F. is reported by Aldridge and Shepherd.⁶ A large amount of data are available involving study of impact testing procedure, welding, effect of heat treatment upon plate as well as castings and piping. All of the conclusions point to excellent properties of various parts of properly heat treated material of this composition.

The low nickel steels when properly deoxidized are satisfactory for temperatures down to at least -100°F. These steels are only slightly more difficult to weld than the carbon steels because of greater air hardening tendencies. Many vessels of the 2¼% nickel composition are in service today at -50°F. This composition, however, is about twice as expensive as carbon steel.

Low Chromium Alloy Steels—Egan, Crafts and Kinzel¹⁰ have made extensive study of the low temperature properties of a great many combinations of low alloy steels with alloying elements of chromium, nickel, manganese, vanadium, molybdenum, zirconium, copper, and silicon. Their conclusions are as follows: 1. Many normalized low alloy steels are suitable for engineering applications down to -112°F. 2. Zirconium and vanadium markedly improve the low temperature impact strength of normalized low alloy steels. 3. When suitably combined with another alloy, chromium, nickel, copper, manganese and molybdenum improve the low temperature impact strength of normalized low alloy steels, the highest values being obtained with the chromium copper combination (0.12% C, 0.75% Cr, 0.50% Cu).

These writers¹ have made further study of the chromium copper combination, in which consideration was given to the effects of various deoxidizers, to mass effect and to properties of welds. It is concluded that:

Notched bar impact values obtained in steels at low temperatures fall into various energy levels. This phenomenon is a function of the nature of the material and is not due to minor variations in the preparation of the test specimens and test procedure.

Chromium-copper aluminum killed low alloy steels are satisfactory for engineering service at temperatures down to -148°F. and may be used in larger sections than plain carbon steel.

Welds produced . . . indicate their fitness for engineering service down to -112°F.

The present authors report that a number of vessels have been built of the chromium-copper aluminum killed steel. However, in practice it was found that commercial heats did not yield as high impact values as indicated by laboratory heats. Further, heavy plates had surfaces which were not wholly satisfactory.

Table III

Tensile Results on Nonferrous Metals and Alloys at Low Temperatures

Authority	Composition	Treatment	Test Temp., °F.	Tensile Strength, psi.	Yield Point, psi.	Elong. % in 2 in.	Red. Area, %		
Russell	Copper	Cold rolled	Room	45,800	43,300	16.0	55.9		
			Liq air	53,000	50,400	19.0	55.4		
		Annealed	Room	32,600	12,700	58.0	44.3		
			Liq. air	50,400	18,300	63.0	68.2		
	Copper 99.75%		64	32,800	7,300	52.0	69.7		
			32	33,700	7,300	51.9	68.5		
			— 22	33,900	7,800	47.5	68.5		
			—112	37,400	8,700	47.1	66.8		
	Naval brass	Rolled	Room	57,100	28,800	47.4	50.5		
			Liq air	81,100	37,200	48.3	48.4		
	Brass #72 Cu 71.6%		64	41,500	9,500	82.6	76.4		
			32	42,800	9,800	79.7	78.7		
			— 22	43,200	10,400	75.9	79.7		
			—112	48,600	12,200	74.5	80.0		
	Brass #60 Cu 63.8% Pb 0.43%		64	46,200	15,400	54.6	60.8		
			32	46,500	14,900	55.4	65.0		
			— 22	46,700	14,700	65.1	68.5		
			—112	49,800	15,600	65.8	64.0		
	Leaded brass	Rolled	Room	35,600	24,400	17.0	22.2		
			Liq. air	42,800	32,100	13.0	19.0		
	Tin bronze	Rolled	Room	61,600	57,000	36.0	65.4		
			Liq. air	93,200	71,800	56.3	58.0		
		Cast	Room	40,200	18,600	31.3	36.7		
			Liq. air	45,300	30,500	15.3	24.6		
Aluminum bronze	Cast	Room	70,300	29,000	33.3	32.6			
		Liq. air	85,900	42,600	24.9	22.4			
	Forged	Room	88,900	47,900	45.2	46.9			
		Liq. air	112,500	84,900	38.4	42.1			
Silicon bronze	Rolled	Room	67,500	34,100	49.0	45.2			
		Liq. air	88,100	39,700	51.3	41.3			
Manganese bronze	Cast	Room	68,500	31,600	39.2	32.5			
		Liq. air	82,700	40,800	26.3	25.8			
Ni 68% Cu 29%	Not rolled	Room	91,500	44,100	45.7	66.9			
		Liq air	135,500	70,800	53.5	67.0			
Ackerman	Ni 68% Cu 29%	Forged	70	80,200	..	42.0	71.0		
			32	83,000	.....	44.0	..	
		Annealed	10	84,400	.....	42.0	...	
			— 20	86,800	.....	47.0	..	
		Forged	—310	130,000	..	32.0	72.0		
			Annealed	—310	117,600	50.7	75.3	
		Russell	Nickel	Hot rolled	Room	93,400	54,400	32.7	45.5
					Liq air	122,500	81,800	46.7	57.2
Ni 99.8% Fe 0.15%	Annealed		77	62,000	....	23.5	75.0	
			—301	86,000	.. . .	22.0	58.0	
	Hard drawn 93% Red.		77	133,000	.....	1.06	58.0	
			—301	155,000	.. . .	3.12	54.0	
Nickel silver	Cold rolled		Room	73,800	69,300	21.5	54.3		
			Liq air	93,700	80,500	35.5	62.6		
	Annealed		Room	64,900	29,500	46.8	62.3		
			Liq. air	83,000	38,200	56.8	69.5		
	Cast		Room	40,300	16,800	40.5	39.2		
			Liq. air	49,200	23,900	32.7	30.2		
Aluminum Alloy	Cast		Room	18,100	7,600	8.8	10.2		
			Liq. air	17,800	8,100	7.0	7.3		
Aluminum Silicon alloy	Cast		Room	17,300	9,200	4.9	5.2		
			Liq. air	19,600	9,600	3.7	4.7		
Duraluminum		Room	57,800	35,400	26.5	27.0			
		Liq. air	71,800	42,700	28.0	28.7			
Molybdenum 99.9%		Annealed	77	29,500	.. . .	18.7	63.0	
			—301	41,000	.. . .	18.5	44.0	
		Hard drawn 93% Red.	77	49,000	.....	2.0	32.0	
			—301	63,000	.. . .	6.0	28.0	
		Annealed	77	63,000	.....	0	0	
			—301	96,000	.. . .	0	0	
		Drawn at 2370°-2190°F.	77	148,000	.....	4.7	68.0	
			—301	212,000	.. . .	0	0	

Accordingly, about ¼ % nickel was added to the chromium-copper composition and surface defects were eliminated together with improvement in Charpy impact values. Table V shows the relation between normalizing temperatures from 1650-1900°F., followed by stress relieving, microstructure, and low temperature impact properties from +70° to -148°F. Weld data are also given. Best values at -148°F. are obtained when normalizing is carried out slightly above the upper critical point. The heat affected zone values are superior to base metal proper at lowest temperatures of impact testing. Weld test data of more recent origin than values given here prove that 10 ft.-lb. at -150°F. are met.

Low Alloy Steels—Herzig and Parke,¹¹ in attempting to determine what steels could meet an arbitrary minimum Charpy strength of 10 ft.-lb., when tested at low temperatures encountered in service, obtained data on the following S.A.E. compositions: 4130, 4140, 4615, 4640, 4815, 4340, 4015, 2330, 3135, 3240, 6145, and 1045. Specimens were tested after three heat treatments, normalizing at proper temperature, quenching and tempered to 200 and 300 Brinell. The beneficial effect of heat treatment was shown, also the superiority of alloy steels to the carbon steel. It was observed that the element molybdenum appeared more effective in improving impact strength at low temperatures when used in conjunction with nickel or chromium or both, especially in the normalized condition. It was concluded that only steels 4615 and 4815 were satisfactory (in excess of 10 ft.-lb. Charpy at -94°F.) as normalized, while in the 200 Brinell condition all steels except 1045 had satisfactory low temperature impact strength. In the quenched and tempered to 300 Brinell condition, all steels except 4015, 3135, and 1045 had satisfactory subzero impact properties. The normalized and 300 Brinell steels were tested at -94°F. minimum, while the quenched and tempered specimens were tested as low as -310°F.

A nickel-molybdenum-vanadium steel¹² used in cast valves is reported to be excellent for shock resistance at subzero temperatures. Heat treatment is drastic and consists of "an homogenizing treatment followed by an oil quench and high temper." Properties given are: Room temperature, tensile strength 107,000 psi.; yield point 88,000 psi.; elongation 22% in 2 in.; reduction of area 61%; and Charpy impact at -150°F. 20 ft.-lb.

High Chromium-Nickel Steels—The high chromium-nickel austenitic steels retain notched bar toughness down to extremely low temperatures. Colbeck, MacGillivray, and Manning¹³ report the following.

C	Composition, %		Room Temp.	Izod Impact Resistance in ft. lb. at			Soaked in liquid air ^a
	Ni	Cr		-85°F.	-184°F.	-292°F.	
0.11	10.0	14.7	116	99	86	80	79
0.11	10.5	15.6	113	...	...	86	70
0.11	10.1	18.3	114	118	108	100	100
0.11	12.0	12.7	118	118	99	102	95
0.11	12.0	14.7	117	118	118	98	96
0.11	11.5	16.2	118	118	...	118	118
0.11	13.8	12.2	111	118	117	102	103
0.11	14.0	14.2	117	118	117	116	104
0.11	15.9	12.3	115	117	118	118	118
0.45 ^b	10.2	13.8	61	...	...	14	...
0.06 ^c	10.5	13.45	117	118	...	118	117

^aTested at -292°F. after soaking in liquid air for from 7 to 14 days.

^bThis steel contains 3.65% manganese.

^cThis steel contains 4.07% manganese

Russell and Welcker¹⁴ obtained the following results on a chromium-nickel steel:

Charpy Impact Resistance, ft.-lb. at °F.

C	Ni	Cr	Condition	Room Temp.	+32	-4	-40	-76	-112
0.09	9.24	17.54	Annealed	80	78	77	78	81	82
			Cold Worked	35	33	31	30	29	29

High Nickel Steels—Chevenard's tests made on a Fremont machine using test bars 35 x 10 x 8 mm. with a notch 1 mm. deep are presented graphically in Fig. 1. It is apparent that when nickel is present in excess of about 45% there is no decrease in resistance to impact at temperatures at least down to that of boiling

liquid air (-310°F). Such steels are, therefore, suitable for parts of liquid air machines and other applications involving service at subatmospheric temperatures. A steel developed by Chevenard especially for this purpose contains 55-60% nickel, 1-3% manganese and 0.2-0.4% carbon. It is reported to have the following properties at liquid air temperatures: Tensile strength, 114,000 psi.; elastic limit, 57,000 psi.; elongation, 40%; reduction in area, 55%; and Fremont impact, greater than 45 kg-m. per sq. cm.

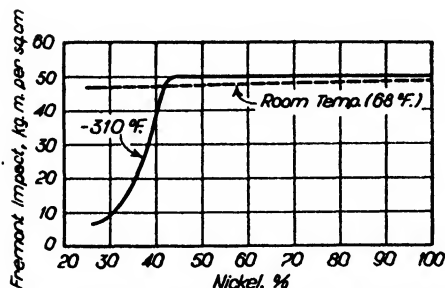


Fig. 1—Effect of nickel upon the Fremont impact resistance of iron-nickel alloys at the temperature of boiling liquid air.

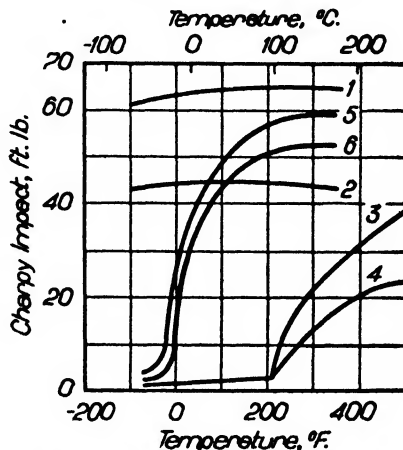


Fig. 2—Charpy impact tests on stainless irons.

1. 18% Cr, 8% Ni, Quenched in Water from 1950°F . 2. Same as 1, Cold Drawn. 3. 18% Cr, Annealed. 4. Same as 3, Cold Drawn. 5. 14% Cr, Annealed. 6. Same as 5, Cold Drawn.

High Chromium Steels—The high chromium compositions should not be used for low temperature service where shock is a factor of any magnitude. Sergeson compares annealed and cold drawn stainless compositions of 18-8, 18% and 14% chromium and shows the low values obtained on the plain chromium compositions (Fig. 2).

Russell and Welcker also bring out the low shock resistance of this group:

Composition, %			Condition	Charpy Impact Resistance in ft.-lb. at—				
C	Ni	Cr		Room Temp.	32°F .	-4°F .	-40°F .	-76°F .— 112°F .
0.07	...	13.85	Annealed	39	38	4	25	1
			Heat Treated*	28	..	..	3, 25, 6	..

* 1850°F . oil; 1025°F . air cooled; 1035°F . water.

Cast Irons and Wrought Irons—Neither of these materials are recommended for low temperature service where shock is liable to be present. Russell² summarizes information on cast iron. Scattered and limited data will be found in the literature on wrought iron.

Nonferrous Materials—Copper, which shows excellent values at room temperature, is little changed in notched bar impact properties at extremely low temperatures. Pure nickel and high nickel-copper alloys also retain good impact properties at low temperatures. Aluminum and brass are likewise little affected as temperature is lowered.

Brinell Hardness—In general the Brinell hardness of metals increases with decrease in temperature, paralleling to some degree the tensile strength. However, a number of nonferrous compositions are distinct exceptions.


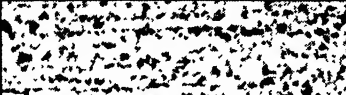
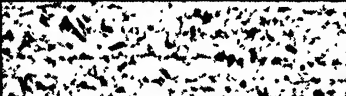
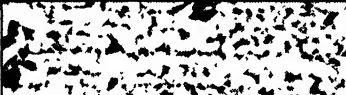




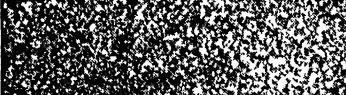

Fatigue—Little work has been done on the fatigue properties of metals at low temperatures. Indication is that endurance limit rises as temperature is lowered.

Testing of Metals at Low Temperatures—General—By far the majority of tests carried out today are made upon impact bars. Many new specifications, particularly those involving welded structures, are requiring that impact tests be met. These

tests are also being used as a check of the suitability of metals and welded structures to operate at low temperatures. Tensile tests are only infrequently made.

Measurement of Temperature—Temperatures down to -328°F . may be measured with calibrated pentane thermometers. Toluol thermometers are also satisfactory for measurement as low as -148°F . Thermometers should be checked frequently over a period of time. They offer the simplest means of temperature determination.

Table V
Microstructure and Charpy Impact Values at Low Temperatures*

*Condition	Etched in 4% Nital-100x	Charpy Impact, Ft.-Lb.									
		+70 °F		-50 °F		-75 °F		-112 °F		-148 °F	
		Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans
R. 1150 °F		66.2	57.3	49.6	38.3	44.9	44.9	38.2	31.2	14.4	19.3
N. 1600 °F R. 1150 °F		64.3	56.4	60.3	41.4	47.1	37.1	43.3	36.2	31.7	26.5
N. 1650 °F R. 1150 °F		60.6	52.1	54.2	39.4	51.6	35.7	38.8	33.1	29.9	24.9
N. 1700 °F R. 1150 °F		61.9	50.5	44.8	33.8	41.9	29.7	32.2	28.8	33.4	20.3
N. 1750 °F R. 1150 °F		63.5	52.5	48.2	38.1	42.5	28.9	36.7	30.8	30.8	24.8
N. 1800 °F R. 1150 °F		63.4	50.8	42.5	37.1	38.4	32.7	37.8	24.7	29.4	3.9
N. 1850 °F R. 1150 °F		60.7	54.4	40.5	33.9	38.9	31.4	34.4	14.0	4.7	18.
N. 1900 °F R. 1150 °F		58.5	47.9	37.7	28.2	33.9	29.4	10.3	28.2	1.9	1.7
Weld R. 1150 °F		23.6		19.4		17.3		16.3		10.8	
Zone Adjacent to Weld R. 1150 °F		50.7		35.6		48.2		44.4		37.2	

*R=Stress Relieved, N=Normalized

*Composition: C 0.10, Mn 0.68, Si 0.21, Cr 0.77, Cu 0.58, Ni 0.63. Plate was $1\frac{1}{4}$ in. thick.

Some prefer to use copper constantan or iron constantan thermocouples. This means is the most accurate. Practically all laboratories use thermometers for routine work.

Methods of Cooling for Low Temperature Testing—For attaining desired low temperatures there are three general methods of cooling which may be used: 1. Controlling the temperature of an entire room. 2. Circulating a cold medium around the specimen before and during the cooling while test is being made. 3. Immersing specimens in a cold medium of controllable temperature, then transferring quickly to testing machine.

The method of cooling depends upon the type of test to be carried out and the temperature it is desired to attain. Obviously the first scheme mentioned will probably give the most accurate results. However, it is the most complex and in most cases is not necessary. Choice of cooling method is also related to length of time required in testing. Where a test can be carried out in a few seconds, such as in a single blow impact test, the third method, which is the simplest, should be used. Only in impact testing may this method be used, as in other tests length of time involved is sufficient to cause considerable temperature rise in a short space of time. It has been shown that where tests are made in seven seconds or less, no appreciable rise in temperature occurs. In tests where plastic deformation occurs temperature rise results and should be considered in interpreting results.

For impact testing the authors use (a) Acetone and dry ice, to $-100^{\circ}\text{F}.$; and (b) Propane and liquid nitrogen, for lower temperatures.

Mechanical Working—No specific studies have been made, but it has been general experience that wrought materials are superior to castings, after best heat treatments are carried out.

Heat Treatment—Proper treatments improve impact values of practically all steels. The more drastic the heat treatment the lower the temperature at which notched bar values fall off, therefore, quenching and high tempering the pearlitic steels gives superior impact values to normalizing.

The present writers were able to obtain more than 75 ft.-lb. at $-75^{\circ}\text{F}.$ on a Charpy keyhole specimen of rimmed steel when it was water quenched in $\frac{1}{2}$ in. sq. section, but when treated as a $1\frac{1}{2}$ in. plate values were extremely low at this temperature.

Microstructure—There appears to be a relation between impact values on notched bars and actual grain size. Sergeson shows that impact specimens of wrought iron broken at $-4^{\circ}\text{F}.$ broke along the grain boundaries with practically no distortion of adjacent grains, whereas at room temperature and higher considerable distortion was apparent in the microstructure.

Melting History—Effect of melting practice in low carbon steels is given by Epstein in Fig 3:

Proper deoxidation has been shown to be of great importance in making carbon and low alloy steels. Aluminum killing in particular is beneficial. Killing with silicon alone has not been found to be as effective as when aluminum or other deoxidizer is also used.

Kinzel and co-workers point to the effectiveness of aluminum, zirconium, vanadium and columbium.

Mass—Since the relation exists between impact values and grain size, it is to be expected that mass is a factor. Many compositions which are suitable in small cross section are not acceptable in larger masses. The effect of mass, may, of course, be overcome in degree by heat treatment.

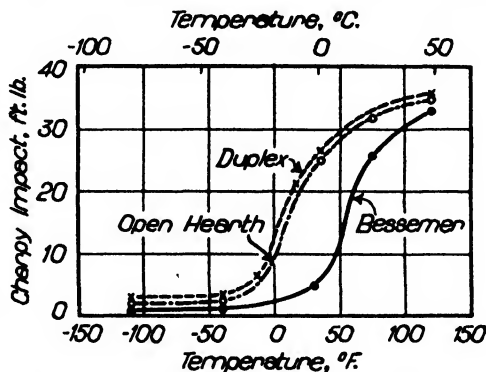


Fig. 3—Low temperature impact properties of carbon structural steels made by various processes.

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Fluidity of Metals

By Charles W. Briggs*

The term "fluidity" refers to the property of a metal which allows it to flow freely and evenly into a mold and fill it before such freezing occurs that would offer an obstruction to its further flow. It is a property sometimes referred to as "castability," "runnability," "flowing power," or "fluid life." "Fluidity," which is the word often preferred, has the disadvantage that in the past it had a specific physical meaning; namely, the reciprocal of the coefficient of viscosity. However, in recent literature the term "coefficient of liquidity" is preferred for this constant, thus allowing the broader field to be covered by "fluidity." There are many, however, who have not accepted the term in its new sense as it is believed that old associations stand in the way of its adoption, and hence the terms given above are often preferred.

When using "fluidity" in its broader aspects, it must be remembered that it should by no means be identified with viscosity. The viscosity of a fluid in the physical sense is concerned with movements in the interior of the liquid, and thus at a given temperature it is a definite physical constant. The viscosity test, which is rather simple and accurate at relatively low temperatures, is exceedingly difficult to perform at the higher temperatures required by molten iron and steel. Foundrymen have, therefore, found it necessary to devise a more simple method for the study of fluidity. In general, this test consists of pouring molten metal into sand molds which contain a cavity in the form of a spiral. This test is concerned primarily with the fluid life of the metal and measurements refer both to the metal and to the mold.

The fluidity or fluid life of metal is dependent on two major factors; (1) properties of the metal, and (2) variables of testing. The factors relating to the metal are those of viscosity, surface tension, surface films, gas content, suspended inclusions, and the mode of solidification and crystallization. The second set includes the form of the test piece, the casting head, the properties of the mold, the rate of pouring, and the degree of superheat.

Properties of the Metal—Viscosity—There is quite a general belief that molten metals differ widely in viscosity, and that metals that flow poorly have high viscosity. In reality, the viscosity of metals is very low, the kinematic viscosity being less than that of water in all cases investigated.¹ Also, since viscosity changes only slightly with change of temperature, it is really a negligible factor in casting. It is unnecessary to go into the details of the methods employed in measuring viscosity. It may be pointed out, however, that there are two main methods of study. In one case liquid metal is allowed to flow under a constant head through a capillary tube and in the other some form of torsional pendulum is used. The first can be applied only to metals of low melting point since the capillary tube is constructed from glass or quartz. The second method may be used at relatively high temperatures with a fair degree of success since the apparatus consists essentially of refractory cylinders or discs suspended in the molten metal operating in torsional oscillations. Studies on tin and lead,² various brasses, bronzes, and copper,³ and cast iron⁴ have been undertaken by the torsional pendulum method.

A critical review of the published data on viscosity was prepared by Andrade.⁵ In this he develops a new theory of the inner mechanism of the viscosity of liquids which has enabled him to calculate η with close approximation of the experimental values for a number of metals. These may be listed as follows:

Substance	At atmospheric temperature	η -Poise
Water	Just above the melting point	0.0105
Mercury		0.021
Lead		0.028
Tin		0.020
Copper		0.038
Iron		0.040

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It may be concluded, therefore, that the viscosity of metals is only a small multiple of that of water; and that the kinematical viscosity (or viscosity divided by density), on the basis of which the effects of stresses due to viscosity in modifying the existing motion of a fluid may be compared, is considerably lower than that of water. It is therefore evident that the viscosity of metals plays only a minor part in their casting behavior, and that the effects which have been attributed to viscosity are mainly due to other causes.

Surface Tension—When molten metals are poured into a sand mold, the mold surface is not wetted.¹¹ The rise of steel in a narrow channel is impeded by the surface tension of the liquid metal. This effect becomes less marked as the diameter of the passage is increased.

Values have been tabulated by Bircumshaw⁶ of the surface tensions of some of the common metals, at temperatures not much above their melting points.

Surface Tension of Some Common Metals

Metal	Temperature °C.	Surface tension (dynes per cm.)
Antimony	640	350
Bismuth	269	378
Lead	327	452
Mercury	20	465
Tin	232	526
Cadmium	320	630
Zinc	419	758
Silver	998	923
Copper	1131	1103
Gold	1120	1128
Iron (2.2% C)	1420	1500
Iron (3.9% C)	1300	1150

The deductions that may be drawn from this table are that: (1) the surface tension of metals increases as the melting point increases; (2) from the figures for the two alloys of iron and carbon, steel has a higher surface tension than cast iron; and (3) since the surface tension of water at 20°C. is only 81, the values for metals are relatively high.

It has also been determined that, in general, surface tension diminishes, as a rule, with increasing temperature.

A high value of surface tension has the effect of increasing the pressure required to cause the metal to enter and flow along a narrow channel, but the direct effect of the true surface tension of many metals is almost overshadowed by the effect of surface films whose influence is equivalent to that of greatly increased surface tension.

Surface Oxide Films—It has been found that surface films affect the flowing power, especially of nonferrous alloys. In a study on brass ingots, Genders and Bailey¹⁰ showed that the oxidation of a stream of molten brass by contact with air gives rise to a surface film of zinc oxide which raises the apparent surface tension of the metal, restricts the flow, and is an inevitable cause of ingot defects.

Determinations of the apparent surface tension of oxidized and clean, molten aluminum have been described by Portevin and Bastien.¹¹ They show that the effect of the oxide film is to increase the value nearly three times.

This surface film property of aluminum also affects alloys in which it is present. According to Desch³ the difficulty of casting aluminum bronze is caused by the formation of such a tough skin that it hinders pouring and, by becoming broken into fragments, is entangled in the metal, making a dirty casting.

When the oxide is soluble in the molten metal, no film is formed, so that copper, cast iron, and nickel pour in a clean stream.

According to Greaves¹² there is some evidence which strongly suggests the existence of films in an over oxidized steel killed with aluminum. Such a surface film would reduce the fluidity. A chromium-rich oxide skin on steels is thought to have a marked effect on their fluidity.

Gas Content—One difficulty in applying data relating to the effect of surface tension in the case of a metal flowing in a channel, arises from the fact that the

metal is often not in actual contact with the mold, but is separated from it by a thin layer of gas, either issuing from the metal or arising from the material of the mold. Gases that are given off from metal during its flow through a casting probably increase the resistance to flow. It is also probable, however, that gas issuing from the metal tends to prevent the formation or break up oxide films so that the fluidity is improved.

Suspended Inclusions—Solid matter in suspension causes a rapid rise in the apparent viscosity of a liquid as suspended particles do hinder flow. A liquid in which more than a small portion of particles is suspended will give a higher value than the same liquid free from solid particles.

Fluidity has been attributed by many steel foundrymen to the effect of dissolved oxides. There is no evidence to suggest that oxide in solution would in itself improve the fluidity of cast steel. It may, however, alter the surface tension or produce some effect on surface oxide films.

Solidification and Form of Crystallization—Test on binary alloys led Portevin and Bastien¹⁰ to formulate two laws: (1) Fluidity varies inversely to the interval of solidification. It will be greatest when the melt is homogeneous (as in the case of pure metals, or eutectics), and is least for the saturated solid solutions. (2) Fluidity depends on the crystal form of solidification and is relatively much greater when the liquid forms crystals with convex faces than when it forms dendrites.

The above principles have been confirmed by other workers.

Variables of Testing—*Form of the Test Piece*—Various types of test bars have been used to measure fluidity in the past. However, for a given metal at a given temperature, spiral test bars will be longer and the test more sensitive, as the metal cools more slowly. Therefore, a geometrical form should be adopted of such a section that for a given volume of metal, the minimum surface for contact between the metal and the mold would be presented. For this reason the more recent investigators have used a spiral mold cross section of which approached semicircular shapes.

There are two designs based on the method employed for metal entry; the European design, Fig. 1, wherein a straight down gate is used and the American design, Fig. 2, that employs a horn gate.

Important data, especially on low melting temperature alloys, has been recorded, wherein permanent molds have been used. However, in the last few years sand molds have been used almost entirely since from the point of view of sensitivity, a mold should have the least possible tendency to chill.

Casting Head—One of the essential parts of the mold is the casting head and the metal reservoir. The height of these above the spiral affects the length of the spirals run. A reservoir must be provided to break the fall of the metal from the ladle and to supply an even flow of metal to the mold down gate.

Properties of the Mold—Variations in the temperature of the mold and the state of dryness of the mold affect the length of the spiral obtained. The permeability of the sand should be sufficient to assure an easy escape for the gas produced by the contact of the liquid metal with the mold. In order that an easy escape of gas or air from the mold be assured the end of the spiral should be well vented. The bond strength of the sand should be sufficient to avoid erosion of the sand by the liquid metal. Mold surfaces may cause variations in the length of spiral obtained. Factors that influence the character of the results have been noted to be: (1) grain size of the sand, (2) degree of moisture, (3) mold washes, and (4) surface coatings.

Rate of Pouring—The length of the test bar depends also on the speed of running the metal in the spiral. This speed of course depends on the rate at which the mold is poured. If the pouring rate varies between one test and another, the length will vary in the same way. Exceptional care must therefore be maintained to pour all molds at the same rate (preferably a fast rate) and that the pouring height above the mold will always be the same.

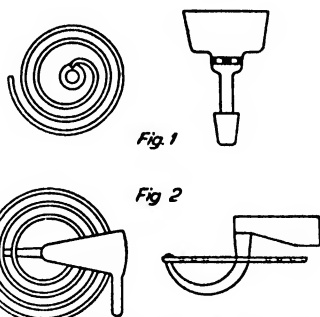


Fig. 1—European type of fluidity mold (Cury).

Fig. 2—The American, or Bureau of Standards type of fluidity mold (Saeger and Krynetsky).

Degree of Superheat—As the temperature of the molten metal is raised the length of the resulting cast spiral is increased. An increased length of spiral with increase of casting temperature does not necessarily imply that the metal is more fluid at the higher temperatures, since the additional spiral length may be due entirely to the increased ranges of temperature, through which the metal cools while it is flowing in the spiral. It should also be emphasized, however, that the degree of superheat may alter the composition of the metal or increase surface oxide films or gas content to such a degree that the spiral length is affected.

Accuracy of Test Methods

Before proceeding to the results that have been obtained by testing methods it is necessary to emphasize that it is difficult to establish a correlation between these tests and actual foundry experience. In fact, little correlation has been established to date. Just why a better correlation has not been established is probably due to the inadequacy of the test methods in that so many factors are involved that only with extreme care is it possible to avoid erratic and meaningless results.

Fluidity of Low Melting Temperature Metals—Most of the experimental work on the fluidity of low melting temperature metals has been carried on by Portevin and Bastien¹³ in a permanent mold. The data, as set forth in Fig. 3, is very complete and is so plotted that fluidity values can be correctly evaluated. In Fig. 4 the curves for zinc and aluminum are plotted directly against the temperature and offer conditions of comparison with those as set forth in Fig. 3.

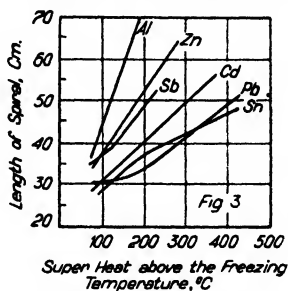


Fig. 3—Fluidity of low melting temperature alloys, permanent mold—spiral cross section area 0.170 sq. in. (Portevin and Bastien).

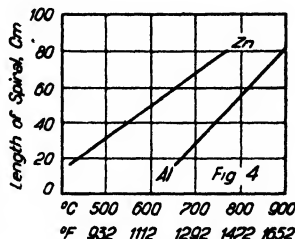


Fig. 4—Fluidity of zinc and aluminum permanent mold (Portevin).

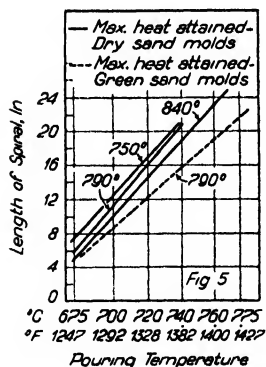
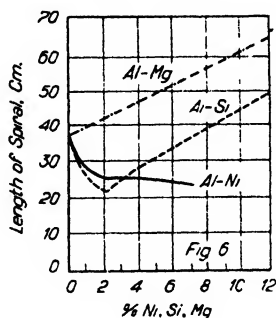


Fig. 5—Fluidity of commercial aluminum sand mold—spiral cross section 0.066 sq. in. (Saeger and Krynetsky).

Fig. 6—The effect of alloying elements on the fluidity of aluminum, permanent mold (Portevin).



The only valuable studies that have been carried on in sand molds, using low melting temperature metals, have been those on aluminum. The results of Saeger and Krynetsky,¹⁴ Fig. 5, are quite typical of what may be expected with commercial aluminum. The authors studied the effect of various maximum heats on the fluidity. They explain the decrease in fluidity, with increase in heating temperature as caused by absorbed gas.

The effect that alloy additions have on the fluidity of aluminum is shown in Fig. 6. It may be noted from this figure that the

addition of some metals brings about a drop in the fluidity such as recorded by nickel. Others may act like magnesium to increase fluidity, and others such as silicon may play a dual role such as to decrease and then increase the fluidity.

The Fluidity of Brass and Bronze—Using the Bureau of Standards mold that they devised, Saeger and Krynetsky¹⁴ studied the fluidity of brass, Fig. 7. They obtained a straight line relation whereas Pilling and Kihlgren,¹⁵ using a modification of the Bureau of Standards mold with a spiral cross section of 0.098 sq. in. as

compared to 0.066 sq.in. of the former, obtained a slight curve for a comparable alloy, Fig. 8.

The Fluidity of Cast Iron—Studies on the fluidity of cast iron have been carried on by various investigators¹ using the permanent mold and sand molds of the European and American type. The most complete set of data, however, have been prepared by Perin and Berger.¹⁰ In Fig. 9, the relation between temperature, fluidity, and carbon content is portrayed. It may be seen from this diagram that if the casting temperature is kept constant, the fluidity increases with the carbon content up to the eutectic concentration (4.3% carbon), then decreases at higher carbon contents. Also, in the hypoeutectic region, there is a sudden increase in fluidity around 4.0% carbon.

Of course there are several constituents in cast iron other than iron and carbon. The influence of these elements on the fluidity of cast iron has also been investigated by Berger. Due to the fact that the additions of phosphorus and silicon influence the temperature of the liquidus, the fluidity comparisons are rather complicated, and for exact information the reader should turn to Berger's original work. However, for those interested in the study of irons, a general law may be formulated as follows: The eutectic mixtures are those which possess the greatest

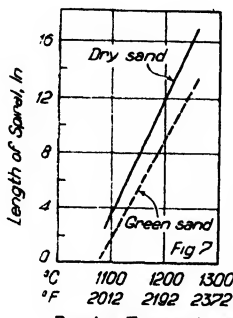


Fig. 7—Fluidity of brass—virgin metal, copper 85%, zinc 5%, tin 5%, lead 5%—spiral cross section 0.066 sq. in. (Saeger and Krynsky).

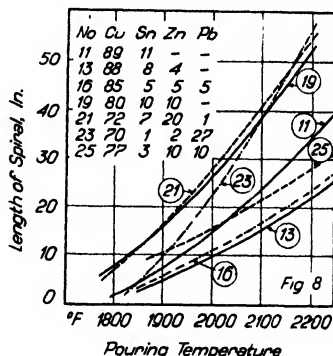


Fig. 8—Fluidity of bronzes—green sand mold—spiral cross section 0.098 sq. in. (Pilling and Kihlgren).

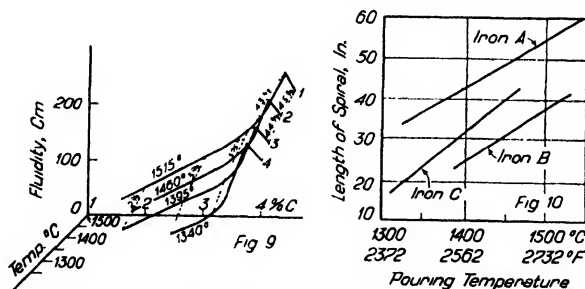


Fig. 9—Diagram showing the relation between temperature °C, fluidity, and carbon content—sand mold—spiral cross section 0.078 sq. in. (R. Berger).

Fig. 10—Fluidity of cast iron—sand mold—spiral cross section 0.066 sq. in. (Saeger and Ash).

	T.C	G.C	CC	Si	S	Mn	P	Liquidus °C.
Iron A	3.56	2.85	0.71	2.62	0.016	0.21	0.85	1170
" B	2.91	2.05	0.91	2.07	0.023	0.17	0.68	1240
" C	3.71	2.81	0.90	1.16	0.054	0.58	0.10	1200

fluidity and, therefore, are those which are most likely to give perfect castings. If the hypoeutectics are considered, the only ones used practically, it is possible to say that the element regulating fluidity is carbon, next is phosphorus, and in a certain measure (under 1.00%) silicon. As to manganese, its influence on fluidity is of little importance. The amount and direction of its influence are essentially a function of the composition of the metal considered. Since, however, the modern commercial trend is toward the low carbon metals the fluidity of cast iron would depend more upon the increment in temperature above the liquidus than on the other recognized controllable factors.

Three commercial cast irons have been investigated by Seager and Ash¹⁷ and these are shown in Fig. 10. These authors state that the running qualities of these irons were dependent upon the liquidus temperature and apparently were not influenced by any previous maximum heating temperature prior to pouring of the fluidity test at a lower temperature. For a chosen pouring temperature, the heats of iron having the lower liquidus temperature have superior running qualities.

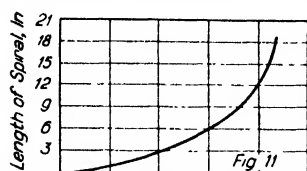


Fig. 11—Fluidity of an iron-carbon alloy—0.71% carbon taking the solidus as zero fluidity—sand mold—spiral cross section 0.091 sq.in. (Andrew, Percival, and Bottomley).

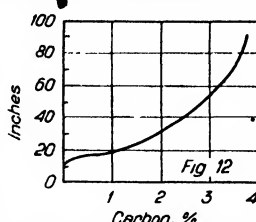


Fig. 12—Fluidity of iron-carbon alloys at 1600°C. (2912°F.)—sand mold—spiral cross section 0.091 sq.in. Andrew, Percival, and Bottomley).

He found that in the case of cast iron poured into a steel spiral mold that he could increase the length of the spiral from 51 centimeters to 81 centimeters by varying the mold coatings. The order of progressive increase was (a) linseed oil, (b) iron oxide, (c) graphite, (d) black lead, and (e) a thin layer of soot from an acetylene flame.

The Fluidity of Steel—There is little valuable information on the fluidity of steel, and that which is available is based on so few points that the curves so constructed may not be justified. In a study of iron carbon alloys, Andrew, Percival, and Bottomley¹⁸ predict the fluidity of several carbon steels. In Fig. 11 is presented a fluidity temperature curve of 0.71% carbon alloy, wherein the liquidus is taken as zero fluidity. Also, Fig. 12 shows the fluidity curve of iron carbon alloys at 1600°C.

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Powder Metallurgy

By Charles Hardy* and Clarence W. Balke**

Definition—Powder metallurgy is the art of making objects by the heat treatment of compressed metallic powders with or without the addition of a nonmetallic substance. It may be applied to a single metal powder or to complex mixtures and the pressing operation may be carried out at ordinary or elevated temperatures. In many cases the results obtained by the use of this method are identical with those obtained by the orthodox methods of melting and casting. In many other instances, however, properties are developed which heretofore were unattainable.

Advantages of Powder Metallurgy—1. This method alone has made possible the production of refractory metals in useful forms. The extremely high melting points of such metals as tungsten, molybdenum, and tantalum forced the development of this process for their preparation in the form of workable ingots. Even if it could be produced commercially, the brittle, coarse grained tungsten made by fusion would be of little value. The nature of the method makes it possible to produce special forms of these metals, such as the nonsag variety of tungsten used in lamp filaments. This is accomplished by the use of certain materials added prior to the sintering operation. In short, the entire development in the field of refractory metals and their carbides in the form of cemented material has made the practice of this art a necessity.

2. The finished product contains the metals in the exact proportions desired. For this reason the composition of alloys can be consistently reproduced. For example 90-10 bronze, and 80-10-10 bronze, can be made of metal powders having a uniformity of composition unapproachable by foundry methods.

3. This process reduces or eliminates impurities introduced by conventional methods. The high purity obtainable in metal powders is retained. Iron may be produced from powder having a great purity and contaminated with manganese, phosphorus, silica or sulphur very slightly, if at all.

4. Aggregates or mixtures can be made of metals which are immiscible in the liquid state or which have widely divergent melting points. Important examples are lead and copper, copper and chromium, copper and tungsten, or copper and molybdenum. The last two compositions are used in the form of welding electrodes or switch contacts handling heavy currents. Good thermal and electrical conductivity is supplied by the copper constituent, and resistance to wear and high temperature is furnished by the tungsten.

In many examples of this type at least one of the constituents of the mixture may be fused during the heat treating operation. Localized alloying on the surface of the unfused grains may take place. Examples of this type are the hard cemented carbides and alloy magnet materials.

5. The method makes it possible to produce metals in which a nonmetal is uniformly disseminated. Current collecting brushes for dynamos and motors are made in this way from mixtures of copper and graphite. Under this heading bearings and bushings must be mentioned specifically since their production accounts for the consumption of large quantities of metal powders. The bearings which are used on a large scale are mixtures of copper, tin and graphite.

6. The dimensions of finished articles may be held within close limits. The pressing dies may be made with a high degree of accuracy, and after heat treatment the precision of the pieces may be increased by striking or coining. Articles so made compete with die castings. It has been found that the precision of the dimensions desired can be controlled to narrow limits, and with the use of coining presses, an accuracy of .001 in. is readily obtained for quite a number of metals or alloys. Even narrower limits have been secured by repressing and coining. Those practiced in the art have found that the type of die, type of powder, length of time of heat treatment and temperature of sintering can be so controlled that contraction or distortion can be held within narrow limits.

7. Economies in production can be effected in many cases. Materials are not lost during the manufacturing operations. When the conventional methods of melting, casting and forging are employed, losses occur due to slag and oxide formation and material may be removed by cropping, removal of flash, or by trimming. These losses may frequently reduce the weight of the finished product to $\frac{1}{4}$ that of the

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material used. With such losses eliminated the more expensive metal powders may be employed to produce finished products on a competitive basis.

8. Special structural effects can be obtained which are not possible in the melting and casting process. Useful bimetal can be made. A layer of iron powder and one of nickel may be converted into a composite ingot by pressure. This can be heated and rolled to produce thin plate or sheet in which the two layers are perfectly welded together. The composite electrode of tungsten and copper may be considered an example under this heading. However, the most notable example of this type of work is the porous bearing. The method makes it possible to produce these bearings having a high degree of porosity of an interlocking character, permitting them to retain appreciable amounts of oil.

9. Lower temperatures than those previously required are often sufficient for the fabrication of certain materials; for example, platinum, iron-nickel-cobalt alloys and the refractory metals.

10. The method makes it possible to work with accurately controlled atmospheres. A neutral, inert or reducing atmosphere may be employed, or heat treatment may be carried out in a vacuum. Tantalum and columbium are heat treated in vacuum.

Limitations and Disadvantages of Powder Metallurgy—Obviously, powder metallurgy does not furnish the solution to every metallurgical problem. It has certain limitations, and even where applicable, difficulties may be encountered.

1. Except in the few cases where masses of metal powder can be heat treated without previous compression, the high pressure required to form the pieces establishes a definite limitation to the application of the process. This limitation is physical in character and resides in the special molds and heavy presses required to compress the powders. As the power of hydraulic presses is increased, larger and larger pieces may be handled, but in such cases the cost of the equipment may become excessive.

2. Many powders have a distinct tendency to cling to the walls of the die as the pressure is built up. This results in an uneven pressure throughout the mass and tends to limit the depth of the die which may be employed.

3. In some instances difficulty is encountered controlling the particle size of the powder. This should be considered merely a disadvantage and not a fatal limitation of the method.

4. Because of the great surface of metals in a finely divided state, difficulties arise due to the action of air and moisture. Occasionally these may be sufficiently great to warrant the provision of air conditioned rooms in which to carry out the operations.

5. In producing a new product considerable experimental work is still required, due to lack of knowledge concerning the welding and adhesion characteristics of the various metals with each other.

Metals Produced in Powder Form—Many metals are now obtainable in powder form but not all of them are of value in the practice of this art. The metals in general use are listed below:

Metal	Purity	Apparent Density
Aluminum	99% plus	0.75-1
Antimony	99% "	2.-2.50
Bismuth	99.90% plus	
Brass	70% Cu-30% Zn	
	65% Cu-35% Zn	
	90% Cu-10% Sn	
Bronze	99.90%	2.8-3.5
Cadmium	99.50% plus	2.5-3.5
Chromium	98.00% min.	
Chromium	98.00% plus	
Cobalt	99.8% "	
Columbium	99.60% "	2.-4.
Copper		
Gold		
Iron	99.50% "	
Iron (hydrogen reduction)	99.90% "	
Lead	99.90% "	4.6
Manganese	98.00% "	3.-6.5
Molybdenum	99.90% "	4.-5.
Nickel	99.65% "	2.5-3.5
Palladium	Pure	
Silicon	97.00% "	.50-.70
Silver		
Tantalum	99.8% "	5.3-6.0
Tellurium	99.00% "	

(Continued)

Metal	Purity	Apparent Density
Tin	plus 99.80%	1.5-2.75
Titanium	92.98% "	
Tungsten (hydrogen reduction)	99.00% " W	9.-10.
Tungsten (carbonyl reduction)	98.00% " W	
Vanadium	88.95% "	
Zinc	99.00% "	2.5-2.75

Practically all metal phosphides can now be made in powder form
COATED POWDERS—Silver coated nickel, molybdenum, copper, and copper coated silver and lead.

The above metals are available in various mesh sizes. The user, however, usually specifies 100, 200, or 300 mesh. Special requests calling for 25%, 50% or even all through 325 mesh can be met. For special purposes material much finer than that indicated here can be obtained by air separation, elutriation, or by other methods. Powders have been actually produced showing a maximum grain size less than 1 mill.

Production of Powders—Metal powders can be produced by various methods such as grinding, stamping, precipitation, atomizing, spraying, electrolysis, condensation, or reduction. The selection of the method to be used for a given metal will be determined, among other considerations, by its chemical characteristics and the nature of its compounds. Metal oxides can be reduced in hydrogen or with controlled atmospheres. The rate of heating and the rapidity of gas flow may be regulated to produce powders of varying particle size. Common examples of metals so made are copper, nickel, cobalt, molybdenum, and tungsten. On the other hand the oxides of tantalum and columbium are not reduced by hydrogen. Powders of these metals are made by the electrolysis of fused salts. In other cases, electrolysis of aqueous solution may be used. Some metals such as gold, silver and the members of the platinum group may be precipitated from the solutions of their salts by the addition of suitable reducing agents. Considerable quantities of iron and nickel powders are made by the decomposition of their carbonyls. In some cases calcium hydride is employed as the source of nascent hydrogen used in the reduction of such refractory oxides as, for example, chromium oxide, titanium, and zirconium oxides.

Characteristics of Metal Powders—The results obtained in the practice of this art will depend, among other things, upon the purity and physical characteristics of the powders used. In many instances it is necessary to maintain the amount of objectionable impurities below definite limits, while in other cases, beneficial impurities are added to the powder mixtures. Metals, in a finely divided condition, carry appreciable quantities of gas either dissolved or as surface films, and this fact must not be overlooked. In some instances the presence or absence of a given impurity of the order of a few hundredths of 1% determines whether the powder is usable or not.

The physical characteristics of the powders are also of great importance. These characteristics concern mainly the shape or structure of the particle itself and the particle size and the range of particle size. The shape of the particles is determined mainly by the method employed in their manufacture. Aluminum powder made by granulation is quite different from that made by stamping. Copper powder made by reduction is distinctly different from that made by electrolysis. The shape of the particles of metal powders produced by condensation, as in the case of zinc, or by the decomposition of their carbonyls, as in the case of iron or nickel, is distinctly spherical.

Since the physical characteristics of the powders often determine their fitness for use, they are subjected to careful tests and examination. Where the powders are sufficiently coarse the particle size and the particle size distribution may be determined by the use of metal sieves. However, this method is not applicable for particles finer than 400 mesh. (The diameter of a particle passing a 300 mesh sieve is about 53 microns.) In the case of finer powders, microscopic examination may be employed, or a measurement of the light blocking action of the powder in suspension in a liquid may be measured. This is especially true in the case of finished powders employed in the hard carbide industry where the particle size may range from 1-5 microns, or finer. The following table gives the relation between the micron, millimeter, and inch:

1.0 micron = .001 mm.	0.001 inch = 0.0254 mm.
1.0 inch = 25.4 mm.	0.0001 inch = 0.00254 mm.
0.1 inch = 2.54 mm.	0.00005 inch = 0.00127 mm.
0.01 inch = 0.254 mm.	0.00004 inch = 1. micron

It is frequently desirable to determine the apparent density of the powder, otherwise known as "loading weight." A common method used for this purpose is to determine the volume of a given weight of powder gently tapped down in a graduated cylinder, or it may be determined by a Scott volume meter. If the latter method is used the powder is allowed to drop through baffle plates into a cup or box of known volume. The powder is carefully scraped off level with the top of the box and weighed. A number of factors other than particle size itself may influence the value of the results obtained in this case. Variations in this loading weight affect the compression ratio when the powder is pressed. The physical characteristics of the powders determine the "flow factor" which may be defined as the weight of powder which will flow through an orifice of given diameter in one minute. This characteristic is of special importance where the pressing operation is carried out automatically, and the dies must be filled by the flow of powder from a hopper. Flow meters are also employed to determine the speed with which a certain weight of powder will travel in specially constructed equipment. Finally, it may be stated that in the case of any given application of powder metallurgy, either all or most of the following properties must be taken into account and held under control: Particle size, particle size range, apparent density, flow factor, shape of particle, cohesive ability, chemical purity, and oxide content.

Mixing of Powder—Where a pure metal is under production this operation is not necessary except in cases where it is desirable to mix together lots of powder having different mesh sizes. The powders are usually mixed in tumblers or ball mills and in some instances the operation is carried out in the presence of a reducing gas to prevent oxidation. Where the specific gravity of the various components of a mixture are quite different, this operation must be carried out in such a way as to produce the greatest possible homogeneity. The time required may vary from a few minutes to as much as 24 hr., or in the case of hard carbide compositions where a grinding operation is also involved, to a number of days.

Compression—The powders may be pressed either hot or cold, but in the majority of cases the operation is carried out at room temperatures. The powder is pressed in dies made of hardened steel, selected to have as low a coefficient of friction as possible. In some cases where small pieces are pressed from highly abrasive powders, the dies are made of hard carbide compositions. The depth of the die will depend to a certain extent upon the compression ratio of the powder, and this is usually in the neighborhood of 3 to 1. In some cases where fine powders are used, the compression ratio may be as high as 6 to 1, or even 8 to 1. The presses employed may be of the hydraulic, cam, friction or knuckle type, and may be equipped with single or multiple dies. As a rule, the pressures employed vary between 5 and 100 tons per sq.in.

The pressing operation may appear quite simple yet it may become troublesome in certain cases. Dies should be made with a high degree of precision and in a great many cases a die with a slight taper will be of great advantage as the amount of pressure needed to eject the compressed piece is in this case only a small part of the pressure exerted in compression. The presses which are now used on mass production are cam presses, friction presses, and hydraulic presses. In the case of hydraulic presses it was found that the slow compression and the pumping operation added to the difficulties and created slipping and entrapped air. A number of hydraulic presses are now built which work with a double reservoir or accumulator and give a rapid stroke allowing 20 and 30 cycles per min. The difficulties which were formerly experienced due to the differential of density of the compressed parts have been largely overcome. Presses and dies are now built in such a way that the percentage difference in density is reduced to nonobjectionable values.

Heat Treatment—Except where this is done simultaneously with the pressing operation, the pressed pieces are given an appropriate heat treatment. This may be carried out in furnaces having an inert atmosphere or in a neutral or reducing gas, or in vacuum. The temperature employed is determined by the metals under treatment and by the characteristics desired in the finished product. In the case of pure metals and in many combinations of metals no part of the material is melted during this heat treatment. In some cases, however, where a small amount of relatively low melting point metal is used in conjunction with a high melting point metal, the lower melting point metal may be fused. This occurs during the heat treatment of hard carbide compositions.

No fixed rule can be laid down as to the temperature to be employed in the treatment of alloys. In general, the temperature used in such cases is about two thirds

that of the melting point of the alloy. In the case of pure refractory metals which are usually heated by the passage of an electric current through the pressed bars, the temperature at the core of the bar is brought close to the melting point of the metal.

Many things may take place during this heat treating operation. Gas may be absorbed or eliminated. Oxide impurities may be reduced. Diffusion of one metal into another may occur and grain growth take place to an extent depending upon the nature of the metal and the temperature employed, and the duration of the heat treatment.

The residual porosity in the heat treated specimens depends largely upon the nature of the material used and the physical characteristics and the chemical purity of the powder. The amount of porosity can be determined approximately by comparing the density of the material with that of the same material in the cast or highly worked condition. In many cases it is desirable to reduce the porosity as far as possible. There are cases, however, where porosity is desirable and is intentionally created within the heat treated specimens. This applies particularly to the so-called oil-less bearings which are produced by the methods of powder metallurgy. Porosity is insured in this material by mixing with the powder volatile salts or low boiling point metals which evaporate on heat treatment, leaving the space they occupy as pores, and if properly carried out, the porosity will be interlocking in nature.

Final Treatment—In some cases the heat treated objects will be the final product. In other cases the material is machined to size or may be subjected to a compression or coining operation to increase the accuracy of the dimensions and improve the surface structure of the metal. In other cases the method produces heat treated ingots, which are subjected to the same mechanical operations that would be used in the case of cast materials.

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Hydrometers*

Baumé Hydrometers—For liquids heavier than water—This hydrometer was originally based on the density of a 10% sodium chloride solution which was given the value of 10° and the density of pure water which was given the value of 0°; the interval between these two values was divided into 10 equal parts. Other reference points have been taken with the result that so much confusion exists that there are about 36 different scales in use, many of which are incorrect. In general a Baumé hydrometer should have inscribed on it the temperature at which it was calibrated and also the temperature of the water used in relating the density to a specific gravity. The following expression gives the relation between the specific gravity and several of the Baumé scales:

$$\text{Specific gravity} = \frac{m}{m - \text{Baumé}}$$

$m = 145$ at 60°/60°F. (15.56°C.) for the American Scale

$m = 144$ for the old scale used in Holland

$m = 146.3$ at 15°C. for the Gerlach Scale

$m = 144.3$ at 15°C. for the Rational Scale generally used in Germany

Also see the table for conversion to density and Twaddell Scale.

For Liquids Lighter Than Water—Originally the density of a solution of 1 gram of sodium chloride in 9 grams of water at 12.5°C. was given a value of 0° Baumé and pure water a value of 10° Baumé. The scale between these points was divided into ten equal parts and these divisions were repeated throughout the scale giving a relation which could be expressed by the formula: Specific gravity = $145.88 \div (135.88 + \text{Bé.})$, which is approximately equal to $146 \div (136 + \text{Bé.})$ Other scales have since come into more general use, such as that of the Bu. of Standards, in which the specific gravity at 60°/60°F. = $140 \div (130 + \text{Bé.})$ and that of the American Petroleum Institute (A.P.I. Scale) in which the specific gravity at 60°/60°F. = $141.5 \div (131.5 + \text{Bé.})$.

Twaddell Hydrometer—This hydrometer, which is used only for liquids heavier than water, has a scale such that when the reading is multiplied by 5 and added to 1000 the resulting number is the specific gravity with reference to water as 1000. To convert specific gravity at 60°/60°F. to Twaddell degrees, take the decimal portion of the specific gravity value and multiply it by 200; thus a specific gravity of 1.032 = $0.032 \times 200 = 6.4^\circ$ Twaddell. Also see the table for conversion to density and Baumé scale.

Hydrometer Conversion Tables

This table gives the relation between density (cgs.) and degrees on the Baumé and Twaddell scales. The Twaddell scale is never used for densities less than unity.

Density	Degrees Baumé Bu. Stand. Scale	Degrees Baumé A.P.I. Scale	Density	Degrees Baumé Bu. Stand. Scale	Degrees Baumé A.P.I. Scale
0.600	103.33	104.33	0.700	70.00	70.64
0.605	101.40	102.38	0.705	68.57	69.21
0.610	99.51	100.47	0.710	67.18	67.80
0.615	97.64	98.58	0.715	65.80	66.40
0.620	95.81	96.73	0.720	64.44	65.03
0.625	94.00	94.90	0.725	63.10	63.67
0.630	92.22	93.10	0.730	61.78	62.34
0.635	90.47	91.33	0.735	60.48	61.02
0.640	88.75	89.59	0.740	59.19	59.72
0.645	87.05	87.88	0.745	57.92	58.43
0.650	85.38	86.19	0.750	56.67	57.17
0.655	83.74	84.53	0.755	55.43	55.92
0.660	82.12	82.89	0.760	54.21	54.68
0.665	80.52	81.28	0.765	53.01	53.47
0.670	78.95	79.69	0.770	51.82	52.27
0.675	77.41	78.13	0.775	50.65	51.08
0.680	75.88	76.59	0.780	49.49	49.91
0.685	74.38	75.07	0.785	48.34	48.75
0.690	72.90	73.57	0.790	47.22	47.61
0.695	71.43	72.10	0.795	46.10	46.49

*From Lange's Handbook of Chemistry, Handbook Publishers, Inc., Sandusky, Ohio

Density	Degrees Baumé Bu. Stand. Scale	Degrees Baumé A.P.I. Scale	Density	Degrees Baumé Bu. Stand. Scale	Degrees Twaddell
0.800	45.00	45.38	1.27	30.83	54
0.805	43.91	44.28	1.28	31.72	56
0.810	42.84	43.19	1.29	32.60	58
0.815	41.78	42.12	1.30	33.48	60
0.820	40.73	41.06	1.31	34.31	62
0.825	39.70	40.02	1.32	35.15	64
0.830	38.68	38.98	1.33	35.98	66
0.835	37.66	37.96	1.34	36.79	68
0.840	36.67	36.95	1.35	37.59	70
0.845	35.68	35.96	1.36	38.38	72
0.850	34.71	34.97	1.37	39.16	74
0.855	33.74	34.00	1.38	39.93	76
0.860	32.79	33.03	1.39	40.68	78
0.865	31.85	32.08	1.40	41.43	80
0.870	30.92	31.14	1.41	42.16	82
0.875	30.00	30.21	1.42	42.89	84
0.880	29.09	29.30	1.43	43.60	86
0.885	28.19	28.39	1.44	44.31	88
0.890	27.30	27.49	1.45	45.00	90
0.895	26.42	26.60	1.46	45.68	92
0.900	25.56	25.72	1.47	46.36	94
0.905	24.70	24.85	1.48	47.03	96
0.910	23.85	23.99	1.49	47.68	98
0.915	23.01	23.14	1.50	48.33	100
0.920	22.17	22.30	1.51	48.97	102
0.925	21.35	21.47	1.52	49.60	104
0.930	20.54	20.65	1.53	50.23	106
0.935	19.73	19.84	1.54	50.84	108
0.940	18.94	19.03	1.55	51.45	110
0.945	18.15	18.24	1.56	52.05	112
0.950	17.37	17.45	1.57	52.64	114
0.955	16.60	16.67	1.58	53.23	116
0.960	15.83	15.90	1.59	53.80	118
0.965	15.08	15.13	1.60	54.38	120
0.970	14.33	14.38	1.61	54.94	122
0.975	13.59	13.63	1.62	55.49	124
0.980	12.86	12.89	1.63	56.04	126
0.985	12.13	12.15	1.64	56.58	128
0.990	11.41	11.43	1.65	57.12	130
0.995	10.70	10.71	1.66	57.65	132
1.000	10.00	10.00	1.67	58.17	134
DENSITIES GREATER THAN UNITY			1.68	58.69	136
Density	Degrees Baumé Bu. Stand. Scale	Degrees Twaddell	1.69	59.20	138
1.00	0.00	0	1.70	59.71	140
1.01	1.44	2	1.71	60.20	142
1.02	2.84	4	1.72	60.70	144
1.03	4.22	6	1.73	61.18	146
1.04	5.58	8	1.74	61.67	148
1.05	6.91	10	1.75	62.14	150
1.06	8.21	12	1.76	62.61	152
1.07	9.49	14	1.77	63.08	154
1.08	10.78	16	1.78	63.54	156
1.09	11.97	18	1.79	63.99	158
1.10	13.18	20	1.80	64.44	160
1.11	14.37	22	1.81	64.89	162
1.12	15.54	24	1.82	65.31	164
1.13	16.68	26	1.83	65.77	166
1.14	17.81	28	1.84	66.20	168
1.15	18.91	30	1.85	66.62	170
1.16	20.00	32	1.86	67.04	172
1.17	21.07	34	1.87	67.46	174
1.18	22.12	36	1.88	67.87	176
1.19	23.15	38	1.89	68.28	178
1.20	24.17	40	1.90	68.68	180
1.21	25.16	42	1.91	69.08	182
1.22	26.15	44	1.92	69.48	184
1.23	27.11	46	1.93	69.87	186
1.24	28.06	48	1.94	70.26	188
1.25	29.00	50	1.95	70.64	190
1.26	29.92	52	1.96	71.02	192
			1.97	71.40	194
			1.98	71.77	196
			1.99	72.14	198
			2.00	72.50	200

Brinell Hardness Test

Preparation of Samples—The surface of all Brinell hardness samples should be flat and reasonably free from scratches. Tests should be taken at a sufficient depth to be representative of the material, or, in the case of large heat treated sections, at such a depth as is representative of a particular zone in the steel.

Ball Diameters and Loads—The diameter of the ball is 10 mm. \pm 0.0025 mm. The weight applied to steels is 3000 kg. for 30 sec.; the weight for softer metals (brasses and bronzes) is 500 kg. for 60 sec. The sample under test should be firmly supported in such a way that the weight acts in a plane normal to the specimen.

Measurements—The diameter of impression used is the average of two measurements at right angles to each other, and the reading error of the instrument should not be more than 0.02 mm.

Formula for Brinell Hardness Numbers—The Brinell hardness number is calculated from the formula as follows:

$$H = \frac{P}{\frac{\pi D}{2} (D - \sqrt{D^2 - d^2})}$$

H = the Brinell hardness number, P = load applied, D = diameter of ball, d = the diameter of the ball impression.

Special Precautions—The Brinell test should not be used on samples of soft steel which are less than about $\frac{1}{2}$ in. thick or on samples so small as to allow flow of metal at the edges as a result of the ball impression.

As there may be some sticking of the mechanism in the hydraulic, hand operated machine, the pumping should be done more slowly as the maximum load of 3000 kg. is approached, otherwise the pressure may go over the load.

Brinell Hardness Numbers—A table of Brinell hardness numbers is given on the next page.

Comparison of Hardness Values—For a comparison of hardness values see the article given at the end of this section entitled "Hardness Conversion Table."

Brinell Hardness Numbers

Brinell Hardness				Brinell Hardness				Brinell Hardness			
Dia. of Impression	No. for Load	Dia. of Impression	No. for Load	Dia. of Impression	No. for Load	Dia. of Impression	No. for Load	Dia. of Impression	No. for Load	Dia. of Impression	No. for Load
in mm.	kg.	in mm.	kg.	in mm.	kg.	in mm.	kg.	in mm.	kg.	in mm.	kg.
2.00	945	158	3.00	415	69	4.00	229	38	143	6.00	96
2.05	899	150	3.05	401	67	4.05	223	37	140	6.05	94
2.10	856	143	3.10	388	65	4.10	217	36	137	6.10	92
2.15	817	136	3.15	375	63	4.15	212	35	134	6.15	90
2.20	780	130	3.20	363	61	4.20	207	34	131	6.20	89
2.25	745	124	3.25	352	59	4.25	201	34	128	6.25	87
2.30	712	119	3.30	341	57	4.30	197	33	126	6.30	86
2.35	682	114	3.35	331	55	4.35	192	32	123	6.35	84
2.40	653	109	3.40	321	53	4.40	187	31	121	6.40	83
2.45	627	104	3.45	311	52	4.45	183	31	118	6.45	81
2.50	601	100	3.50	302	50	4.50	179	30	116	6.50	80
2.55	578	96	3.55	293	49	4.55	174	29	114	6.55	78
2.60	555	93	3.60	285	48	4.60	170	28	111	6.60	77
2.65	534	89	3.65	277	46	4.65	167	28	109	6.65	75
2.70	514	86	3.70	269	45	4.70	163	27	107	6.70	74
2.75	495	83	3.75	262	44	4.75	159	27	105	6.75	73
2.80	477	80	3.80	255	42	4.80	156	26	103	6.80	72
2.85	461	77	3.85	248	41	4.85	152	25	101	6.85	70
2.90	444	74	3.90	241	40	4.90	149	25	99	6.90	69
2.95	429	72	3.95	235	39	4.95	146	24	97	6.95	68

Rockwell Hardness Test

By A. L. Davis*

Principle of Test—Under certain fixed conditions of load the Rockwell tester measures the depth of residual penetration by a steel ball or a diamond cone. The hardness is expressed as a number which is derived by subtracting the penetration from an arbitrary constant. A minor load of 10 kg. is first applied, which seats the penetrator in the surface of the specimen and holds it in position. The dial is then set at the point marked "Set" and the major load applied. After the pointer comes to rest, the major load is removed, leaving the minor load still on.

As Rockwell hardness numbers are based on the difference between the depths of penetration at major and minor load, it will be evident that the greater this difference, the less the hardness number, and the softer the material. This difference is automatically registered when the major load is released (the minor load still being applied), by a reversed scale on the indicator dial, which thus reads directly Rockwell hardness numbers.

Preparation of Surfaces—Surfaces that are ridged perceptibly to the eye by rough grinding or coarse machining offer unequal support to the penetrator. The degree of surface refinement depends on the accuracy required. When testing bar stock or forgings, it is advisable to remove enough of the surface by grinding or machining so that the penetrator will test the true metal underneath. A fairly smooth surface is necessary for accurate work, so the scale resulting from hardening should always be removed before testing. This is particularly true with tool work, as it is often necessary to polish the work with a piece of emery cloth before the proper reading can be obtained.

Thickness of Specimens—For accurate results, the specimen must be of such thickness that the undersurface of the specimen, after testing, does not show a perceptible impression. This thickness will vary greatly according to the hardness of the material tested. The hardest steels give true hardness readings if over 0.027 in. in thickness. Soft material requires greater thickness of specimen, or lighter load, or both.

Curved Surfaces—Results from tests on a curved surface may be in error and should not be reported without stating the radius of curvature. In testing rounds,

Table I
Rockwell Scales

Designation of Scale	Used for	Major Load, Kg.	Type of Penetrator Used	Read on Dial
A	Cold Rolled Strip Steel Case Hardened Steel Nitrided Steel	60	Brale	Black Numbers (outside the graduation)
B	Standard	100	$\frac{1}{16}$ " Ball	Red Numbers (inside the graduation)
C	Standard	150	Brale	Black Numbers (outside the graduation)
D		100	Brale	Black Numbers (outside the graduation)
E	Die Castings and Soft Metals	100	$\frac{1}{8}$ " Ball	Red Numbers (inside the graduation)
F	Annealed Brass	60	$\frac{1}{16}$ " Ball	Red Numbers (inside the graduation)
G	Phosphor Bronze	150	$\frac{1}{16}$ " Ball	Red Numbers (inside the graduation)
H		60	$\frac{1}{8}$ " Ball	Red Numbers

*Prepared for the Hardness Testing Committee by A. L. Davis, Research Engineer, Scovill Mfg. Co., Waterbury, Conn.

The membership of the Committee was as follows: H. M. German, Chairman; C. H. Bierbaum, O. W. Boston, R. C. Brumfield, I. H. Cowdrey, A. L. Davis, and S. L. Goodale.

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the effect of curvature may be eliminated by filing a small flat spot on the specimen.

Recording Readings and Speed of Machine—Every report of a test made on the Rockwell machine must state what scale is used, or its meaning becomes a matter of guesswork. This is done by the use of the designating letter, such as "B," "C."

Fig. 1 shows the approximate relation between Rockwell scales. These curves are correct only for the kinds of metal indicated in Table I and must not be regarded as holding true indiscriminately.

The machine is provided with means for regulating the rate of application of the load, for which the standard speed is 5 sec. when using the 100 kg. load, and 4 sec. with the 150 kg. load. Metals that flow readily under pressure, such as zinc, should be tested under a specified period of time of load application, which should be stated in reporting the results.

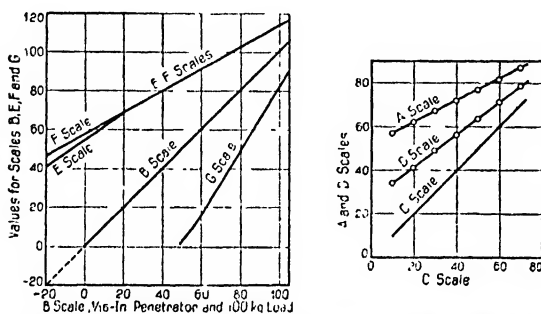


Fig. 1—Approximate relation between Rockwell scales.

Standardization—Standardization of Rockwell machines is secured through the use of standard test blocks obtained from the manufacturer. The machine should check correctly with the standard blocks before being used to test other material. Even when checking satisfactorily with the standard blocks, high readings may yet result if the specimen is placed so that the penetrator strikes upon a spot previously tested. Low results may be obtained when testing thin specimens upon a hollow anvil (that is, an anvil which has been indented while testing very thin specimens or through other abuse). Specimens that are too thin may give either high or low results (though more frequently high) and a rough or corrugated surface will give inaccurate readings.

When testing even thick specimens with rough surfaces, low readings may result due to surface irregularities of the specimen on the face which rests against the anvil. It is almost as important to have this face free from rough grinding-marks and their irregularities as it is the face being tested.

Homogeneity of Specimens—The Rockwell tester measures the hardness of the specimen at the point of penetration, but the reading is also influenced by the hardness of the material under the impression. For example, in testing the hardness of carbon steels (using cone penetrator) the actual depth of penetration is about 0.0027 in., while the effects of penetration extend about 10 times this depth, or 0.027 in., so if a softer layer is located within this depth the impression will be deeper and the apparent hardness less. Therefore, due regard for this condition must be had when testing material with a superficial hardness, such as case hardened work.

To secure the average hardness of materials such as cast iron with graphite particles, or some nonferrous metals whose crystalline aggregates are greater than the area of the penetrator, a penetrator of sufficient size may be used to overcome the local or grain hardness.

Comparison of Hardness Values—For a comparison of hardness values see the article given at the end of this section entitled "Rockwell, Scleroscope, Brinell Conversion Table" and also the curves given at the end of this section entitled "Comparison of Hardness Values."

Precautions

1. As vibrations cause fluctuations in the readings, a location should be selected where there is freedom from vibration. The heavy jars from steam hammers are especially to be avoided.
2. Be careful not to damage the penetrator or the anvil by forcing them together when a specimen is not in the machine.
3. If the anvil has been indented by contact with the penetrator, the readings on thin specimens will be inaccurate.
4. Apply the minor load carefully so as not to overshoot the mark. If the specimen is raised so as to start to pick up the major load, the test should be abandoned and a new one made.
5. The loading lever should be brought back gently, not with a jerk.
6. If the specimen is so thin that there is a perceptible imprint on the back after testing, the hardness shown is not reliable, although sometimes of use for comparison of metal of same thickness.
7. Check the machine regularly every day by use of standard blocks, and record the results for reference.
8. If the test is used on case hardened steel, the accurate hardness is not shown unless the hard layer is at least 0.027 in. thick.
9. The plunger of the dial gage must move with absolute freedom. Erratic results may be due to its binding, either sidewise or back and forth.
10. If the bearing screw in the top lever becomes indented by the ball which presses against it, the results will be erratic. In such a case, the screw should be replaced. The new style (floating cap) index screws are constructed upon a new principle. They are supposed never to require replacement.
11. The ball penetrator tends to become flattened by use, especially in testing hardened steels. It should therefore be checked occasionally and replaced when necessary. In the same way the cone penetrator should be examined carefully if results do not check, and should be replaced if found to be blunted or chipped.
12. The rate of load application is adjustable, and should be so adjusted that when no specimen is in the machine, at least 5 sec. are consumed in the travel of the weight from its initial to its final position, using the 100 kg. load. If the 150 kg. load is used, the time should be 4 sec. as a minimum. The time in actual operation of the machine will be more than 4 sec., because of the added resistance of the test piece; and the time required for the pointer to come to rest will vary from 3 sec. on fully hardened steel to 8 sec. on fully annealed brass. With the softer nonferrous metals, normal indentation by the penetrator is followed by flow or "creep," which results in low readings. Hence the major load should be removed as soon as the pointer visibly comes to rest.

Superficial Hardness Tester—The Rockwell Superficial Hardness Tester is intended exclusively for hardness tests where only very shallow penetration is possible and to determine the hardness of the specimen close to the surface. It is used for testing nitrided steel, safety razor blades, lightly carburized work, brass, bronze, and sheet steel.

Principle of Operation—Instead of the 10 kg. minor load and the 60, 100, and 150 kg. major loads of the regular Rockwell, the "Superficial" applies a minor load of 3 kg. and major loads of 15, 30, and 45 kg.

Penetrators—The regular $\frac{1}{8}$ in. dia. steel ball penetrator is used in the Superficial tester on brass, bronze, and unhardened steel, and it is designated as T. On hard steel surfaces (nitrided steels) the sphero-conical diamond Brale is used and is designated as N.

Designation of Readings—The readings are recorded by giving the major load which is followed by the designation for the penetrator used (N for the diamond Brale penetrator and T for the $\frac{1}{8}$ in. ball penetrator). This is followed by the dial reading. The established prefix symbols are as follows:

Brale N	$\frac{1}{8}$ " Ball
15-N	15-T
30-N	30-T
45-N	45-T

The scale pan applies 15 kg. major load and each of the weights 15 kg., so the major load may be 15, 30, or 45 kg.

Precautions—Although not necessarily polished, the specimens to be tested on the Rockwell Superficial must have a smooth finish. There must be no dust, scale or any particles on the under surface of the specimen or on the anvil, because any sinking of the specimen when under the testing load will add to the actual penetration as measured by the dial gage.

Scleroscope Hardness Test

The principle employed in the scleroscope is the drop and rebound of a diamond tipped hammer. This hammer drops by the force of its own gravity from a fixed height upon the test specimen. The resulting rebound, of the model "C" instrument, is then read against a graduated scale.

The scale consists of units which are determined by dividing the average rebound from quenched high carbon steels into 100 equal parts.

With the model "D" instrument, the readings are recorded on a dial after the strike and rebound of the hammer. The dial hand remains fixed indefinitely or until released for another test.

The scleroscope should always set level when taking a reading, as indicated by the bob rod on the side of the tube barrel. When the instrument is on its clamping stand it is levelled by the tripod screw. When on the swing arm and while using free handed it is levelled by the aid of the plumb bob.

The instrument in addition to setting level should be held steady or free from lateral movement or shocks. When the instrument is moved or shaken roughly enough to rattle the plumb bob it has a marked effect upon the accuracy. These conditions should be observed when free hand tests are made; otherwise, the reading will be low.

Surface of the Specimens—The specimen to be tested, especially when the reading is high, should always have a smooth surface. The higher the readings, the smoother must be the surface. The principal objection to a rough surface is the fluctuation caused in the reading. The reading taken from a rough surface will be lower than the true result.

The surface obtained by using a medium fine emery wheel is usually satisfactory for hard metals, and the surface obtained with a No. 2 or No. 3 file for soft metals will be smooth enough. Mill scale, blister, rust, and decarburization should, of course, always be removed by grinding. The preparation of hardened specimens by grinding, especially with a fine emery wheel, should be done carefully to prevent tempering the surface.

Reading the Scleroscope—The reading is the height of the first rebound noted on the scale at the top of the hammer.

To locate the range, look for the rebound when hardened steel is tested between 90-100; for medium hard around 50, and for soft metals around 10 or 15, and so on. When the range is found, do not look above the range, but rather, a few points below, for if the rebound is higher it is easily determined, but if it is less it will not come within the range of focused vision and will be missed.

The light should fall downward on the instrument so that the glistening on the top of the hammer will act as a guide, and the top of the hammer should be kept bright, as this aids materially in the ease of reading the rebound. A strong light is recommended, either artificial or daylight.

The Hammer Diamond—The hammer diamond of the instrument should be tested regularly on standard blocks. It is advisable to check the instrument in the range in which it is to be used, because sometimes an instrument may read correctly at one hardness and incorrectly at another. If it reads low, particularly on a hard standard block, it is due either to a roughened or worn point. The diamonds are not polished but are reasonably smooth. A magnifying glass will disclose whether the failure to check is due to the condition of the diamond or to some other cause.

The Magnifier Hammer—The regular hammer when used on very soft metals has a comparatively limited rebound. The magnifier hammer is made with a larger point area, which enables it to rebound higher, thus magnifying small but significant variations in readings. This is a special hammer and is more of a laboratory convenience.

The Lens and Pointer Needle—The scleroscope is provided with a lens and a pointer needle which together may be adjusted to any part of the scale. By setting the lens and the needle at the figure that the first rebound shows, slight variations above and below are easily noted. The lens is used principally on soft metals.

The Sound of the Hammer—A little practice will soon disclose, when light or under-weight specimens are tested under the scleroscope, that two different sounds

may be produced. A solid dull thud indicates that the specimen has been clamped solidly and the test is perfect. A hollow ringing or jingling sound indicates that the specimen is either not properly supported, due to excessive warping or lack of parallelness, or, if straight, is not properly clamped. In these instances, the test is useless and should be corrected.

Small and Thin Specimens—Under-weight samples, such as sheets, thin flats, small balls, rods or wire, that can be made to lie flat under the drop hammer, should be clamped down to make certain that no air space or intervention of dirt may cause a variation in the accuracy.

Large or Over-Weight Masses—Large masses to be tested are easier to mount and depend less on the scleroscope anvil for their under support. Accurate results are obtained without clamping large specimens but by placing them on an iron bench plate when testing.

Testing Near the Edge—On small specimens little or no difference is noted by testing near the edge, if the specimens are flat and clamped rigidly. On other shapes, such as cylindrical specimens, particularly when hollow, a certain amount of drop in the reading is noted, due to the lack of mass and improper under support. These errors can be corrected by the use of suitable clamping devices.

Precautions

1. Do not allow the hammer to strike more than once on the same spot or too near it, because the readings will be of no value.
2. Mount specimens as solidly as possible.
3. Testings of small pieces are best conducted in a bench vise by using the swing arm. Use soft steel copper or lead jaws whenever possible.
4. Average readings should be taken in all cases where local characteristics are not being studied.
5. The operating mechanism should be properly lubricated with a light, high grade oil. On the bulb machine no oil should be permitted to enter the glass tube. With the dial machine oil must be kept away from the clutch mechanism.
6. The hammer should fit in the tube properly.
7. Keep the instrument clean at all times.

Low Readings May Be Due:

1. To friction from dirt in the glass or on the hammer.
2. To clogging the vent holes in the bottom cap of the barrel which causes interference with escape of air under the falling hammer.
3. To a loose diamond. (This may be determined under a magnifying glass by tapping the stone lightly.)
4. To being out of plumb.
5. To striking a glancing blow when impacted surface is not level.

High Readings May Be Caused:

1. Under exceptional conditions by wear on the diamond point. Hammers that read too high should be redressed and restandardized. This can be determined by use of standard blocks.
2. When the valve ball becomes clogged with dust so that it cannot set properly some air will enter the glass tube chamber, which causes the hammer to drop with a greater velocity, with the result that abnormally high readings will be obtained.

Comparison of Hardness Values—For a comparison of hardness values see the article on Hardness Conversion.

The Monotron Hardness Test

By O. W. Boston*

Description—The monotron is a hardness testing machine which registers on a dial the load required to produce a definite penetration of a body.

Two indicating dial gages are used, one for measuring the pressure and the other for measuring the depth of penetration in both soft and hard materials.

Principle of Test—Penetration is first made to a predetermined standard depth by aid of a compensated depth micrometer indicator. The hardness number is then read from the pressure scale in terms of kg. per unit area while the load is still on. This feature serves to eliminate errors caused by confusion with elastic recovery and provides for testing other materials in addition to metals.

Upon releasing the load, the depth indicator returns toward zero to the extent of the elastic recovery of the test specimen. The remaining divisions above zero indicate the degree of permanent deformation. By exceeding the recommended standard depth of penetration, ductility and point of plastic flow of metals and compositions are determined.¹ The effect of time is of importance here and is also readily observed.

Preparation of Surfaces—In the use of the standard spherical impresser points, the surface may be either prepared or unprepared.

On prepared surfaces (not polished) the hardness test is made without the use of prepressure, so the pressure indicator hand normally rests at zero. The zero for the pressure scale is really $\frac{1}{2}$ kg. above to offset the weight of the pressure bar. Impressions thus made to the adopted standard depth of penetration, $9/5,000$ in. may be checked up when desired for diameter with a measuring microscope to test the accuracy or adjustment of the machine.

Testing on unprepared surfaces, such as when scaly, rough, or decarburized, may be done with accuracy by the use of prepressure, such as setting the starting point of the pressure hand from 10-20 kg. or more below zero, thus cutting through the irregular surface. When the pressure hand has been brought to zero, the depth indicator hand is then required to penetrate further to the standard testing depth of $9/5,000$ in. and the unit pressure above zero on the pressure scale is taken as the quantitative hardness of the specimen.

Tests on Thin Specimens or Finished Surfaces—When testing sheet a minimum thickness of 0.020 in. is required to give hardness values without anvil effect. Sheets down to 0.010 in. in thickness may be tested although an allowance has to be made for anvil effect. On thinner specimens it is necessary to pile up sheets to make up the required thickness of 0.020 in.

When the test must be substantially nondestructive, only part of the standard penetration is taken, such as $\frac{1}{2}$, in which case the pressure readings are multiplied by three to obtain the full depth values and standard hardness numbers.

Tests on Nitrided Steels—When the case of nitrided steels is of insufficient thickness to permit the application of the fixed load the hardness measurement may be accomplished by taking the sum of three readings of three divisions each, rather than a single reading of $9/5,000$ in.

Monotron Scales—The standard test is made with the diamond ball impresser which is $\frac{1}{2}$ mm. in dia. and penetrates to a depth of $9/5,000$ in.; with this is used scale M-1, which reads directly in Brinell numbers. This test measures the hardness of all metals from the softest to the hardest, including nitrided surfaces and

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The personnel of the Hardness Testing Committee is as follows: H. M. German, Chairman; C. H. Bierbaum, O. W. Boston, R. C. Brumfield, I. H. Cowdrey, A. L. Davis, and S. L. Goodale.

¹By point of plastic flow is meant the degree of overload under a hardness test penetrator which would cause additional penetration without additional load if extra time is allowed.

By compositions is meant some nonmetallic materials which, when submitted to penetrational strains, will flow when stressed beyond the elastic limit in proportion to the time allowed, something like, but more exaggerated than in metals.

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cemented tungsten carbide, without any special compensative adjustment of the machine or changing of points.

The term "Monotron Hardness" indicates that the $\frac{1}{4}$ mm. dia. diamond point was used. It is designated as 100 kg. Monotron, or Monotron Diamond Brinell. Larger spherical penetrators are used in dead soft metals because the $\frac{1}{4}$ mm. dia. diamond necessarily gives small values. Hence $\frac{1}{8}$ in. and $2\frac{1}{2}$ mm. dia. cemented tungsten carbide points are used for these metals. Results from these tests are referred to as scales M-3 and M-4 respectively. Scale M-2, using a 1 mm. diamond ball, is not in common use. To penetrate hard metals, a point of this size is too large.

Comparison of Hardness Values—For a comparison of hardness values see the article given on this subject at the end of this section.

Vickers Diamond Pyramid Hardness Test

By S. L. Goodale,* B. B. Rosenbaum,* and Howard Scott†

Principle—The principles involved in testing hardness by the Vickers diamond pyramid and the Brinell methods are practically identical. A predetermined load is impressed at a point upon the specimen. The ratio of the impressed load to the area of the resulting indentation gives the hardness number. The loaded indenter point is lowered upon the specimen gradually, and at a diminishing rate. This application and the removal of the load, after a predetermined interval, are controlled automatically.

Vickers Indenter—As the Vickers indenter is a diamond, it can be used in testing the hardest steels and remains practically undeformed.

The diamond indenter is accurately cut and polished to the shape of a square-based pyramid. Therefore, the impressions are extremely well defined and geometrically similar, irrespective of depth. Although a similar effect can be obtained by use of a conical indenter, the square impression of the pyramid is much more easily measured (across the diagonals) than the diameter of a circular impression.

The surface for testing must be flat and well polished, as scratches or grooves may cause difficulty in reading due to defective corners in the impression.

Measurements—The measurements are taken by means of a specially constructed ocular micrometer which is fitted with knife edges rather than the usual hair lines. The readings are taken from actual figures at the side of the ocular, thus eliminating the possible error of miscounting the divisions on a small scale.

Application of Load—The internal mechanism of the Vickers instrument consists mainly of a weight operated cam. The speed of rotation of this cam is controlled by an oil dashpot, and the movement applies the load to the diamond indenter. The same cam applies, removes, and controls the duration of the load. The load is light, varying from 1-120 kg. according to requirements. It is applied and removed automatically. One movement of a starting handle releases the mechanism, and the depression of a foot pedal restores it to its original position. An audible click informs the operator of the duration of the test. It is recommended that the time of load application be standardized at 10 sec.

Upon lowering the stage, the microscope may be swung into a position over the impression. The measuring microscope is of the angular type, centers automatically, and is capable of measuring to 0.00005 in.

The Impression—The impression appears as a dark square on a light ground. The measurements are taken across the diagonals of the square between the knife edges in the ocular. There are three knife edges: One is fixed, another movable by means of a micrometer screw connected to the counting mechanism, and the third provided for rapid readings to specified limits. The left hand corner of the impression is set to correspond to the fixed knife edge, the movable knife edge adjusted to coincide with the right hand corner of the impression, and the reading taken by reference to the indicator at the side of the ocular. The actual hardness figure is then found from a chart or calculated by a simple formula.

Hardness Numbers—Hardness numbers obtained with a pyramid indenter are practically constant, irrespective of the load applied. The Vickers and Brinell hardness values on steel are practically identical up to a hardness of about 300. At higher hardness values the Brinell falls progressively lower than the Vickers number, and is not reliable above about 600 Brinell hardness, even with specially hardened balls. This irregularity is caused by flattening of the steel ball under the heavy local loads required for testing hard materials, whereas the diamond shows no distortion.

*Prepared for the Hardness Testing Subcommittee by Prof. S. L. Goodale and B. B. Rosenbaum, University of Pittsburgh, Pittsburgh, and †Howard Scott, Engineer in Charge of Metallurgical Section, Westinghouse Electric & Mfg. Co., Pittsburgh.

The membership of the subcommittee was as follows: H. M. German, Chairman; C. H. Bierbaum, O. W. Boston, R. C. Brumfield, I. H. Cowdrey, A. L. Davis, and S. L. Goodale.

The relations for slide rule calculation of Vickers hardness are:

$$H = 1.8544 \frac{L}{d^2} \text{ where } H \text{ is the Vickers pyramid numeral; } L \text{ is the load in kg.,}$$

and d is the diagonal of the indentation in mm. d is obtained from the ocular reading, r , from the relation:

$$d = 0.002 r \text{ or } 0.001 r \text{ (for } \frac{2}{3} \text{ in. objective), and}$$

$$d = 0.005 r \text{ or } 0.0025 r \text{ (for } 1\frac{1}{2} \text{ in. objective), depending on the constants of the micrometer ocular.}$$

The hardness numeral is calculated from the ocular reading by the following relation:

$$H = 0.4636 \frac{L}{r^2} \times 10^6 \text{ (for } \frac{2}{3} \text{ in. objective, where } d = 0.002 r);$$

$$H = 1.8544 \frac{L}{r^2} \times 10^6 \text{ (} \frac{2}{3} \text{ in. objective, where } d = 0.001 r);$$

$$H = 0.07418 \frac{L}{r^2} \times 10^6 \text{ (for } 1\frac{1}{2} \text{ in. objective, where } d = 0.005 r);$$

$$H = 0.2967 \frac{L}{r^2} \times 10^6 \text{ (} 1\frac{1}{2} \text{ in. objective, where } d = 0.0025 r).$$

Comparison of Hardness Values—For a comparison of hardness values see the hardness conversion table on page 127.

Testing Thin Sheet—This tester can be used on thin sheet because of the accuracy with which the small impressions may be read. Lighter loads are used when testing sheet thinner than about 25 gage.

Advantages—Some of the advantages claimed for the Vickers machine are:

1. The load is uniform, and automatically applied, so that there is no inertia.
2. The duration of the load is uniform, the load being automatically removed at the end of a predetermined interval.
3. The hardest material can be tested accurately because of the diamond indenter.
4. There is very little damage done to the specimen because the impression is very small.
5. Both the "case" and "core" of case hardened steels may be tested, since the impression is only about 0.002 in. deep on hard steels.
6. Only slight resetting is necessary under the microscope.
7. Errors in reading are greatly eliminated, since readings are taken from actual figures rather than from a scale.
8. Specimens with a wide range of sizes can be tested. Specimens up to 13 in. deep, in some cases 17 in., can be accommodated under the indenter.

Disadvantages—A disadvantage attributed to the Vickers machine is that it is more of a laboratory instrument than a shop machine. Strictly speaking, this is not true, for the construction is sturdy, and the operation simple. As the impressions are much smaller than for the Brinell or Rockwell machines, the *surfaces for testing must be prepared much more carefully*. Although the Vickers instrument is definitely a machine of precision, it requires *care* in operation rather than any particular *skill*.

Checking—It is advisable to check the machine occasionally against standard test blocks. In case of failure to check satisfactorily, the trouble may be due to the plunger sticking in the sleeve. Polish the tube or plunger carrying the diamond indenter in a longitudinal direction with dry emery paper (400 C).

Precautions—

1. Apply test only to smooth level surfaces representative of the material.
2. Select the load with regard to hardness and thickness of the piece to be tested.
3. Replace the diamond when it becomes chipped as shown by irregularity of the impression made.
4. Check the zero position of the micrometer occasionally.
5. Adjust the knife edges of micrometer accurately perpendicular to the impression diagonals.
6. Keep the dashpot full of suitable oil to prevent impact loading.
7. Discard readings made on a tilted surface which are indicated by a large difference between the two diagonal readings

The Microcharacter

By C. H. Bierbaum*

Introduction—The Microcharacter offers a method for testing the hardness of microscopic areas or constituents of alloys, exceedingly thin layers of metal, and gradients of hardness.¹ The degree of refinement of this method has been made possible only by the skill of a lapidary, F. F. Gilmore of Boston, who now grinds the diamond to a degree of refinement never heretofore attained. The sapphire was first used, but was found unsatisfactory. The instrument was originally designed for studying bearing alloys;² but now finds general application.

Description—The test specimen must be small (not in excess 1 sq. in. of area). It should have a ground and polished metallographic surface. The specimen should be mounted on an ordinary microscope slide with plastic material in the usual manner. The microscope equipment should be rigid and of the highest order, a 1.5 or 2 mm. oil immersion and a 3 or 4 mm. dry objectives should be provided, also a filar screw micrometer ocular of 15 or 25 X. A vertical illuminator giving ample illumination must be provided. The combination should be such that a single micron (1/1000 mm.) can be measured with a reasonable degree of accuracy. The standard load on the diamond is 3 g. The diamond is ground with three facets making right angles with each other, a solid right angle, the corner of a cube. It is mounted so that the diagonal of the cube is normal to the test surface, with one edge accurately in line of cut. The point of the diamond is sharp and perfect under a magnification of 2000 X.

Operation—The ocular should first be calibrated with a stage micrometer, so that the value of the subdivisions of this ocular scale are known in terms of microns.

Microhardness Numbers

Standard 3-g. Weight

$$\kappa = \lambda^{-2} 10^4 = \text{Microhardness}$$

$$\lambda = \text{Width of Microcut in Terms of } \mu$$

μ	κ	μ	κ	μ	κ	μ	κ
100.0	1.0	14.5	47.6	9.0	123	3.7	730
76.0	1.7	14.0	51.0	8.8	129	3.6	772
64.0	2.4	13.5	54.8	8.6	135	3.5	816
56.0	3.2	13.0	59.2	8.4	142	3.4	865
50.0	4.0	12.8	61.0	8.2	149	3.3	918
47.5	4.4	12.6	63.0	8.0	156	3.2	977
45.0	4.9	12.4	65.0	7.8	164	3.1	1041
42.5	5.5	12.2	67.2	7.6	173	3.0	1111
40.0	6.3	12.0	69.5	7.4	183	2.9	1189
37.5	7.1	11.8	71.8	7.2	193	2.8	1276
35.0	8.2	11.6	74.3	7.0	204	2.7	1372
32.5	9.5	11.4	76.9	6.8	216	2.6	1479
30.0	11.1	11.2	79.7	6.6	230	2.5	1600
28.0	12.8	11.0	82.6	6.4	244	2.4	1736
26.0	14.8	10.8	85.8	6.2	260	2.3	1891
24.0	17.4	10.6	89.0	6.0	278	2.2	2066
22.0	20.7	10.4	92.5	5.8	297	2.1	2268
20.0	25.0	10.2	96.2	5.6	319	2.0	2500
19.5	26.3	10.0	100	5.4	343	1.9	2770
19.0	27.7	9.9	102	5.2	370	1.8	3087
18.5	29.2	9.8	104	5.0	400	1.7	3460
18.0	30.9	9.7	106	4.8	434	1.6	3906
17.5	32.7	9.6	109	4.6	473	1.5	4444
17.0	34.6	9.5	111	4.4	517	1.4	5102
16.5	36.7	9.4	113	4.2	567	1.3	5917
16.0	39.1	9.3	116	4.0	625	1.2	6944
15.5	41.6	9.2	118	3.9	657	1.1	8264
15.0	44.4	9.1	121	3.8	692	1.0	10000

(For a 9-g. weight use $\frac{1}{2} \lambda$)

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¹Trans. A.S.S.T., Jan., 1931.

²Trans. A.S.M.E., 1920, p. 1099.

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The mounted test specimen is then placed on the instrument. A drop of "super-fine" watch oil (can be obtained in the jewelry trade) is placed upon the test surface at the point where the microcut is to begin. The diamond is then lowered upon the test piece into the drop of oil until the suspension arm is horizontal as indicated by its spirit level. The worm gear is then engaged and the test surface slowly moved under the diamond point, making the microcut. After the lubricating oil has been removed and immersion oil applied to the test surface, the width of cut is then examined and measured at points of interest and translated into micro-hardness according to the accompanying formula and table.

Caution—The diamond, the hardest of all known substances, is brittle. Under no conditions should the point of this diamond be brought in contact with another diamond, since an almost insensible pressure upon this exceedingly sharp point produces a load per unit area that is far in excess of the crushing strength of the diamond. It should not be subject to blows of any kind during manipulations. The instrument is not intended for commercial testing; it is for research only, in the hands of a skilled metallurgist or microscopist.

File Hardness Test

By H. T. Morton*

The File Test—To determine whether or not a steel article is "file hard," the handle of the file is grasped in the right hand with index finger extended along the file, and the surface to be tested rubbed slowly but firmly with the sharp teeth. Just as soon as it is apparent whether or not the file will bite, it is removed. The object to be tested may be held in the left hand and rested on a bench or against a stop, or it may be clamped in a vise.

The simplicity and rapidity of this method of hardness testing are strongly in its favor for the control of hard surfaces in production. In the period of a few seconds the tester can determine the hardness of each tooth of a gear, various surfaces of a ball or bearing, or other hardened parts without injury to the surface.

File Hardness or "Scratchhardness"—It has been suggested that the ability to resist a file be called the "filehardness" of a surface. There are grounds for the belief that the degree of filehardness is related to the ability to resist wear and abrasion, for when the file tooth takes hold of the metal it penetrates to a small degree, as well as scrapes and wears away a small portion of the metal—that is, it "abrades" it. This is probably a better approximation for gears and other articles which get a sliding or rubbing action than for cutting tools. Some cutting tools give excellent service, even though less than "file hard."

Factors Influencing Test—Comparisons of filehardness are dependent upon three factors: (1) The size, shape, and hardness of the files; (2) the speed of moving the file across the hardened part and the pressure and angle of the file while moving; (3) composition and heat treatment of the steel being tested.

1. *Size, Shape, and Hardness of Files*—The first item can be standardized by using files made especially for testing, and by making sure that the files are not used after they have become dull. Pieces of steel or samples of the product with the proper hardness and temper so they can just be touched with a new file can be used as gages or master test pieces for the beginner, and later for comparison tests when any doubt exists as to the hardness of the article or the cutting ability of the file. As long as the file will cut the master test piece, it is good to use for testing purposes. The number of times a "single spot" on the file can be used will depend upon the hardness of the articles being tested and the degree of skill acquired by the workmen, but there is always the master test piece to prove the accuracy and cutting ability of the "single spot."

New files to be used for testing should be standard (that is, able to cut a standard hardness block) and uniform (that is, every spot on every file able to cut the block). Such files are procurable from reputable manufacturers.

One manufacturer recommends 10-in. mill bastard files for testing. Another makes the following grades of testing files and describes their uses as follows:

- 6-In. Pillar Testing File No. 0
- 6-In. Pillar Testing File No. 1
- 8-In. Pillar Narrow Testing File
- 6-In. Three-Square Testing File No. 1, ▲

"The pillar type of file is used for testing hardened or tempered steel articles of flat, oblong or square shape, and also the outside surface of round or curve-shaped articles. The 3-square type is used for testing articles which are irregular in shape, and in which there are crevices or grooves. The 8-in. pillar narrow testing file and the 6-in. No. 0 file are better used when testing for absolute hardness, while the finer No. 1 cut is better for use when testing tempered articles."

2. *Speed, Pressure, and Angle of File While Making Test*—The second item influencing the file test is controlled by the skill of the workman. The slower the speed the more accurate is the test, because high speeds will wear off the surface of both the part and the file, thereby giving a false indication of softness. A girl in inspection was able to wear away hardened balls (Rockwell C-64) by moving the file fast enough, while a man applying a heavy pressure at slow speed produced a negligible effect on the same material.

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Shape of the article and angle of contact with the file teeth also influence filehardness. It is easier to "touch" a narrow edge than a wide surface. There is also a noticeable difference in resistance given by a polished piece as compared to a rough surface, and by a dry surface as compared to one wet with oil. Even so, there is seldom any necessity to prepare the surface to be tested, such as by removing all scale; generally the file will remove enough scale to give an accurate test of hardness, provided the part is held rigidly.

3. *Influence of Composition and Heat Treatment*—The third item, namely the composition of steel and its heat treatment, is such that the file is limited to certain very high hardness values, with a minimum of approximately Rockwell C-58-C-60. Its utility on tempered parts might be limited to a still higher range. The writer's experience with standard 10 in. mill bastard files indicates that quenched carbon steel parts of Rockwell C-60 hard will not be cut, while C-58 cuts slowly, and chromium steel parts tempered at 350°F. with a Rockwell of C-62-64 will often cut easily.

A leading American manufacturer states that his files made especially for testing will not cut straight carbon tool steel (Rockwell C-64-C-68) immediately after drastic quenching, but will cut it after tempering to 375°F., even though the Rockwell hardness still measures C-64-C-66.

Soft Spots and Decarburization—For determination of soft areas or depth of decarburization the hardened parts should be clamped in a vise, rather than held in the hand. This insures rigidity and allows the tester to use both hands, and thereby control his applied pressure and speed of stroke in filing away the soft surface metal. Under these conditions the file test is much quicker than microscopic examination or other methods of measuring depth.

Advantage of Test in Hands of Skilled Inspectors—File testing is an art acquired by experience rather than a scientific method. It must be fitted to the needs of the particular product being manufactured and in only a few instances is used as a standard for specifications. The terms of defining it are so flexible, and ordinary files vary so much, that the results are not reproducible enough to be passed between manufacturing plants as a standard. But it can be and is developed in individual factories into an excellent method of determining the hardness of hardened metal products.

The skilled workman who uses a file for testing soon learns to allow for all the factors that might influence the accuracy of the test, and when using standard testing files the file test becomes an extremely useful measure of hardness. The required skill is not difficult to acquire.

Cost of the test is dependent less upon labor costs than upon the life of the files used. When testing parts having narrow contacts with the files, the teeth are worn and broken quickly, thereby allowing only a few strokes to each area on the file, but skilled workmen will be able to use the full width of the file in this manner. For wide specimens the teeth wear more slowly but uniformly, necessitating care in discarding the file when it is too dull for good use.

The rapidity of the file test keeps it as a regular means of testing hardness and decarburization, but it is limited to a small range of usefulness—mostly on hardened parts, not tempered. Whenever it is desired to define the term "file hard," one should specify the hardening procedure on the test block which the file cannot touch.

Reference

W. C. Hamilton, Notes on File Scratch Test, *Metal Progress*, Sept., 1937, p. 265.

Hardness Conversion Table

Introductory Remarks—This table only applies to steel of uniform chemical composition and uniform heat treatment, and is not recommended for nonferrous metals or for case hardened steels.

The descriptive articles in the Handbook on the Brinell, Rockwell, scleroscope, and Vickers hardness testing methods should be referred to, and especially the sections in these articles dealing with the applications and precautions to be taken with these instruments.

Approximate Relations Between Brinell, Rockwell, Shore, Vickers and Firth Hardnesses and the Tensile Strengths of S.A.E. Carbon and Alloy Constructional Steels.

Brinell		Vickers or Firth Dia. Hardness No.	Rockwell		Shore Scleroscope No.	Tensile Strength 1000 psi.
Dia. in mm., 3000 kg. load 10 mm. ball	Hardness No.		C 150 kg. load 120° Diamond Cone	B 100 kg. load 1/16 in. dia. ball		
2.05	898	....	..	...	..	440
2.10	857	....	..	...	...	420
2.15	817	....	..	...	...	401
2.20	780	1150	70	...	106	384
2.25	745	1050	68	...	100	368
2.30	712	960	66	...	95	352
2.35	682	885	64	...	91	337
2.40	653	820	62	...	87	324
2.45	627	765	60	...	84	311
2.50	601	717	58	...	81	298
2.55	578	675	57	...	78	287
2.60	555	633	55	120	75	276
2.65	534	598	53	119	72	266
2.70	514	567	52	119	70	256
2.75	495	540	50	117	67	247
2.80	477	515	49	117	65	238
2.85	461	494	47	116	63	229
2.90	444	472	46	115	61	220
2.95	429	454	45	115	59	212
3.00	415	437	44	114	57	204
3.05	401	420	42	113	55	196
3.10	388	404	41	112	54	189
3.15	375	389	40	112	52	182
3.20	363	375	38	110	51	176
3.25	352	363	37	110	49	170
3.30	341	350	36	109	48	165
3.35	331	339	35	109	46	160
3.40	321	327	34	108	45	155
3.45	311	316	33	108	44	150
3.50	302	305	32	107	43	146
3.55	293	296	31	106	42	142
3.60	285	287	30	105	40	138
3.65	277	279	29	104	39	134
3.70	269	270	28	104	38	131
3.75	262	263	26	103	37	128
3.80	255	256	25	102	37	125
3.85	248	248	24	102	36	122
3.90	241	241	23	100	35	119
3.95	235	235	22	99	34	116
4.00	229	229	21	98	33	113
4.05	223	223	20	97	32	110
4.10	217	217	18	96	31	107
4.15	212	212	17	96	31	104
4.20	207	207	16	95	30	101
4.25	202	202	15	94	30	99
4.30	197	197	13	93	29	97
4.35	192	192	12	92	28	95
4.40	187	187	10	91	28	93
4.45	183	183	9	90	27	91
4.50	179	179	8	89	27	89
4.55	174	174	7	88	26	87
4.60	170	170	6	87	26	85
4.65	166	166	4	86	25	83
4.70	163	163	3	85	25	82
4.75	159	159	2	84	24	80

Figures in italics are an approximation and are to be used only as a guide.

(Continued)

Brinell		Vickers or Firth Dia Hardness No.	Rockwell		Shore Scleroscope No.	Tensile Strength 1000 psi.
Dia. in mm., 3000 kg. load 10 mm. ball	Hardness No.		C 150 kg. load 120° Diamond Cone	B 100 kg. load 1/16 in. dia. ball		
4.80	156	156	<i>1</i>	83	24	<i>78</i>
4.85	153	153	..	82	23	<i>76</i>
4.90	149	149	..	81	23	<i>75</i>
4.95	146	146	..	80	22	<i>74</i>
5.00	143	143	..	79	22	<i>72</i>
5.05	140	140	..	78	21	<i>71</i>
5.10	137	137	..	77	21	<i>70</i>
5.15	134	134	..	76	21	<i>68</i>
5.20	131	131	..	74	20	<i>66</i>
5.25	128	128	..	73	20	<i>65</i>
5.30	126	126	..	72	..	<i>64</i>
5.35	124	124	..	71	..	<i>63</i>
5.40	121	121	..	70	..	<i>62</i>
5.45	118	118	..	69	..	<i>61</i>
5.50	116	116	..	68	..	<i>60</i>
5.55	114	114	..	67	..	<i>59</i>
5.60	112	112	..	66	..	<i>58</i>
5.65	109	109	..	65	..	<i>56</i>
5.70	107	107	..	64	..	<i>55</i>
5.75	105	105	..	62	..	<i>54</i>
5.80	103	103	..	61	..	<i>53</i>
5.85	101	101	..	60	..	<i>52</i>
5.90	99	99	..	59	..	<i>51</i>
5.95	97	97	..	57	..	<i>50</i>
6.00	95	95	..	56	..	<i>49</i>

Figures in italics are an approximation and are to be used only as a guide.

Moh's Scale of Hardness

1 Talc. 2. Gypsum. 3 Calc spar. 4. Fluor spar. 5. Apatite 6 Feldspar. 7. Quartz 8. Topaz.
9 Sapphire 10. Diamond.

Hardness Testing at Elevated Temperatures

By Dr. Oscar E. Harder*

Introduction—Methods have been devised and used to determine the hardness of metals and alloys at elevated temperature, but as yet no standard procedure seems to have been adopted. As a result, many of the data reported in the literature are doubtful, and even the best figures available by different investigators are generally not comparable because of the different procedures used in making the tests. This article briefly reviews the methods that have been used in hardness testing at elevated temperatures and discusses the important factors involved and the precautions to be taken in making such tests.

Testing Methods—For convenience, the procedures that have been used in hardness testing at elevated temperatures may be grouped under 4 methods, as indicated below; they are given in about the chronological order in which they were first used:

A. Ordinary Hardness Test—The sample to be tested is heated to the desired temperature, removed from the furnace, and then tested in the usual way. Generally, the Brinell test has been applied. Obviously, the method is open to the criticism that the indenting ball is cold and, therefore, cools the metal at the contact. The specimen cools during testing and at higher temperatures, if a steel ball is used, it may be softened and deformed.

B. Drop or Impact Hardness Test—This method determines the impact hardness (drop hardness) and then either expresses the results as the work divided by the volume of the indentation ($\text{mm. kg.} \div \text{cu.mm.}$) or by reference to a curve, converts these values into equivalent static hardnesses. This method has been rather extensively used, because the time during which the indenter is exposed to the high temperature is reduced to a minimum. Usually, a ball of 5 or 10 mm. dia. has been used as the indenter and the diameter of the impression measured. In some cases a material of known hardness has been placed back of the ball, so that it also showed an impression as a result of the impact, from which the relative hardness could be calculated. This method is open to the objections that the indenter is cold and that impact hardness values may not be directly comparable to static hardness values.

C. Indenter and Specimen Heated—In this method the indenter and the specimen are both heated to the desired temperature and the test made either by the static or impact method. The cemented carbide ball has made it possible to make the ordinary Brinell test at temperatures extending well into the red heat range.

D. Mutual Indentation—This method is the one most recently reported and employs the mutual indentation produced on 2 cylindrical specimens of the material being tested under selected loads. Its advantages in the procedure described are that indentation is made on 2 specimens of the same material held at any desired temperature. Its disadvantages are that special specimens are required, and a factor must be used to convert the hardness values obtained into standard Brinell values. For extremely hard materials, this method has the further disadvantage that the flattened surface is narrow, even when a load of 3,000 kg. is applied, and for that reason sufficiently accurate readings are difficult to make.

The application of the mutual indentation method of hardness testing at ordinary temperatures has been described by Cowdrey,² and its application to determining the hardness of high speed steels and related alloys at elevated temperatures by Harder and Grove.³

Results of Tests—For complete information on the methods of hardness testing at elevated temperatures and a discussion of the results obtained, a selected list of references is given at the end of this article. See especially references 2 and 5.

Critical Discussion of Methods—It seems obvious that method A cannot be depended upon to give an accurate measure of the hardness of materials at elevated temperatures, and it should not be considered as satisfactory.

Method B may give relative values, but the data available indicate that higher hardness values are obtained by this method of testing at elevated temperatures than by either methods C or D. For that reason it seems that a preference must

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be given to methods C and D to obtain reliable hardness values at elevated temperatures. Method C seems preferable in most respects, because the values obtained are expressed in terms that are widely employed without using a conversion factor, as is required in method D. Method C also makes it possible to use a more conventional test specimen.

Indenters—Because the usual steel balls will be softened at the higher testing temperatures and are therefore, likely to be deformed in testing, even when a new ball is used for each test, as was done by d'Arcambal,³ it seems advisable to limit their use to temperatures below which the indenters will be appreciably tempered. This will limit the use of steel indenters to temperatures of about 400-900°F., depending upon the composition and its resistance to tempering on heating. Perhaps steel indenters should be limited to temperatures up to 400°F.

The sintered carbide ball appears to be usable to a much higher temperature, probably up to at least 1475°F. Likewise, the diamond indenter retains its hardness at elevated temperatures and should be usable up to 1500-1800°F.

In method D, the material being tested is used as the indenter, and there seems to be no difficulty about using the elevated temperatures except that the load applied must be decreased as the temperature increases or as the hardness of the material decreases. Apparently, satisfactory results have been obtained up to 1475°F. with the high speed steels.

Method of Heating Specimens—Obviously, it is necessary to heat the specimens under test throughout to the testing temperature and to hold them at this temperature during the test. For the lower temperatures, water, glycerin, cylinder oil, and possibly a fused salt bath may be used. For the higher temperatures, it is more convenient to use some type of furnace, preferably electrically heated, which can be used to maintain accurately the desired temperature.

Effect of Time at Temperature—For temperatures below the annealing or softening temperatures of the material under test, the time that the specimens are held at temperature is of minor importance. As soon as the testing temperature is above the annealing or softening temperature of a material being tested, the holding time becomes important. For example, Wissler and Day¹¹ made tests on a high speed steel of the 18-4-1 type at 1300°F., in which the specimens were held 20 min., 1 hr., and 1½ hr. and obtained the Brinell hardness of 275, 193, and 175, respectively. At 1100°F., in which the holding times were 20 min. and 1½ hr., hardness values of 495 and 415, respectively, were obtained. The effect of holding time at temperature, which has varied considerably with different investigators, is one of the factors that has contributed to the lack of consistent results at the higher testing temperatures.

Two methods of procedure might be considered; first, the material being tested might be thoroughly annealed or tempered at a temperature at least as high as the testing temperature before it is subjected to the hardness test at elevated temperatures. Under this procedure, the holding time would be of minor importance provided the specimen was heated uniformly throughout.

The second procedure would involve heating the specimen only long enough to bring it to the testing temperature and making the test without establishing equilibrium as to tempering or annealing at the testing temperature.

A combination of these two methods might involve holding for relatively long periods of time at the testing temperature in order to approach an equilibrium condition with reference to tempering and annealing, but since these reactions proceed slowly, it would seem that the testing period would be unduly prolonged in this process.

Time of Application of Load—The behavior of the metals in deforming under load at elevated temperature depends upon the individual metals, that is, as to whether or not they work harden to some extent or whether they are automatically annealed as they are deformed. There seems to be no good reason for making the time of application of the load greater than that at ordinary temperatures, and it would seem that satisfactory results should be obtained with the loads applied for an interval of 30-60 sec. as in ordinary testing.

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Test Specimens

By R. L. Templin*

Introduction—In the determination of the mechanical properties of metals variations in the testing methods used, may and often do, cause variations in the values obtained. Unfortunately the effects of such variations are quantitatively different for many of the present day commercial metals and alloys. Because of these facts, it has long been recognized, though perhaps not fully appreciated, that quite definite methods of testing must be followed if acceptable results are anticipated. Satisfactory methods of testing for metals must give proper consideration to such factors as selection of test coupons, size and preparation of test specimens, axial and uniform loading of test specimens, speed of testing, sensitivity and accuracy of all testing apparatus used, and calculations, plotting or other interpretations based on observed values.

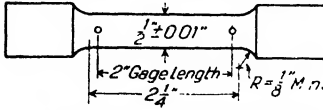


Fig. 1—Tension test specimen for general use in testing metals.

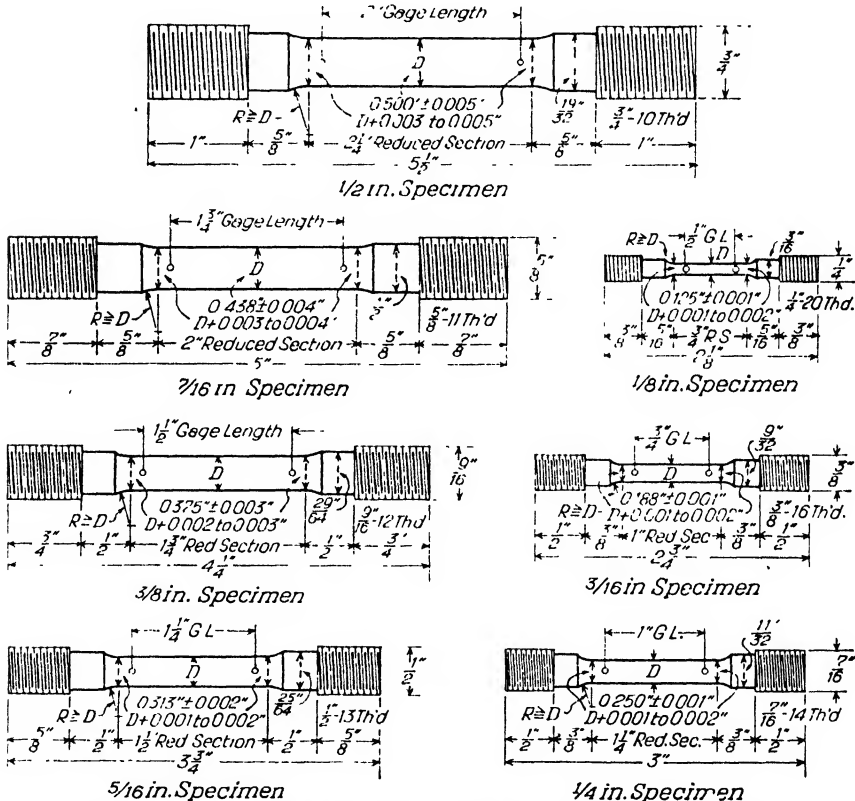


Fig. 2—Various sizes of threaded end, round tension test specimens for metals.

Mechanical property test values for metals obtained in accordance with the best testing methods now in use are, of necessity, empirical in character but have many useful purposes. Some of the more important fields wherein the mechanical property test data for metals are of importance include: Specifications, manufac-

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turing process control, basis of engineering design values, development of new alloys or fabrication processes, and as a basis for comparison with other metals.

Tensile Tests—The generally accepted standard specimens for making tensile tests of metals are shown in Fig. 1-8. The round specimen shown in Fig. 1 is the most satisfactory for ordinary testing purposes where the size and shape of the product will permit of its use. When the product to be tested requires the use of a smaller specimen, and comparable data are desired, a geometrically similar specimen should be used. Various sizes of such smaller specimens, with readily usable gage lengths, are shown in Fig. 2. While these specimens are shown with threaded ends, they may be prepared with plain or shouldered ends to suit the testing apparatus available. In all of the round specimens shown in Fig. 1 and 2, the gage length is equal to 4 times the diameter or $4\frac{1}{2}$ times the square root of the cross sectional area of the reduced portion of the specimen.

The rectangular or flat tensile specimens now in general use for metals are shown in Fig. 3 and 4. The length and width of these specimens are maintained constant within the limits shown, irrespective of the thickness of the specimens. This procedure is followed for practical reasons but makes a satisfactory comparison of elongation values quite difficult, when appreciable differences in thickness are involved, or results from the use of both types of specimens. Other factors remaining constant, the elongation of a ductile metal will vary as some function of the cross sectional area of the test specimen used. Consequently the smaller of the two specimens shown will give lower elongation values for any given thickness of metal. Reduction in area values from thin rectangular specimens are usually not reliable or obtainable because of the difficulties contingent upon their measurement.

Despite the difficulties encountered in making elongation or reduction in area comparisons of metals when using the rectangular or flat specimens, the results obtained with these specimens, especially tensile strength, yield strength (or yield point) and elongation, serve a useful purpose in the manufacture, sale, and use of many metal products.

Other standard types of tensile specimens together with their specific fields of use are shown in Fig. 5-8.

Compression Tests—Compression test specimens for metals are not at the present time as standardized, for example, as the tensile specimens. Tentatively, however, three types are recognized as being suitable for metals. These are shown in Fig. 9. The short specimen is used for compression tests of bearing metals, the medium length specimen for determining the general compressive strength properties and the long specimen for determining the modulus of elasticity of metals. The dimensions suggested for general use are as follows:

Specimen	Dia., in.	Length, in
Short	$1\frac{1}{4} \pm 0.01$	1
	0.798 ± 0.01	2%
Medium length	1 ± 0.01	3
	$1\frac{1}{8} \pm 0.01$	3%
Long	$1\frac{1}{4} \pm 0.01$	12%

Compression tests are appreciably more difficult to make, with satisfactory results, using the ordinary type of universal testing machine, than are the tension tests.

This is so because in the compression tests eccentricities in loading tend to increase as the load on the specimen is increased, whereas in the tensile tests the eccentricities tend to decrease under increasing load. This is especially so for loads in the plastic range. In spite of these difficulties, compression tests can be carried out successfully if proper attention is given to details of apparatus and procedure.

Shear Tests—Although a variety of shear tests are made on metal products no generally recognized standard methods or specimens have been adopted. One type of shear test is the torsional in which either a solid or tubular specimen is used. Solid specimens are often tested full size, but for more accurate results they may be reduced in lateral dimensions as in the case of the tensile specimens. The tubular or thin wall, hollow specimens are the more suitable for obtaining shearing strength values for metals, largely because the cross section of the specimen has more nearly uniform stress than in the case of the solid specimen. For ultimate shear strength determinations, the hollow specimens should have short reduced

sections of about $\frac{1}{2}$ diameter, and a diameter to thickness ratio of from 10-12. For determination of shear modulus and yield strength values, a hollow specimen having a length of at least 10 diameters and a ratio of diameter to wall thickness of not over 10, for its reduced section, is to be preferred. The actual dimensions of the specimen used may well be chosen to suit both the size and type of testing machine available, as well as the product to be tested.

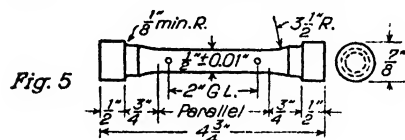
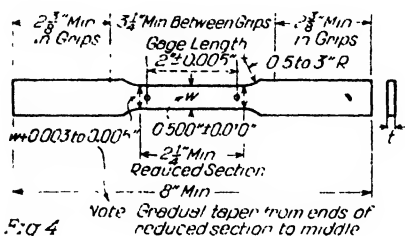
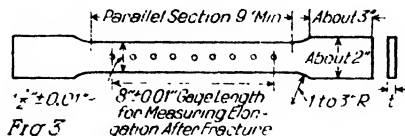


Fig. 3—Tension test specimen for plate material ranging in thickness from about $\frac{1}{4}$ - $1\frac{1}{2}$ in. For plate over $1\frac{1}{2}$ in. thick the specimen may be machined to not less than $\frac{1}{4}$ in. thickness or a standard round specimen used.

Fig. 4—Tension test specimen for sheet metals ranging in thickness from about 0.01 to, but not including $\frac{1}{4}$ in.

Fig. 5—Type of tension test specimen particularly adapted to hard steels and brittle materials.

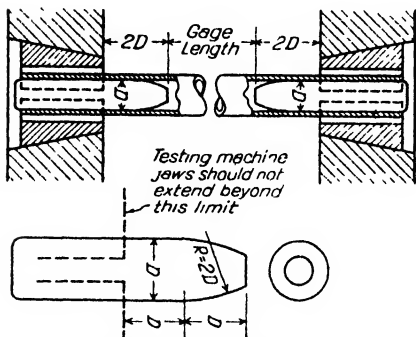


Fig. 6—Tension specimen for metal tubing ranging in size up to about 2 in. outside diameter but particularly for sizes 1 in. outside diameter and less. For larger sizes cut-out specimens as shown in Fig. 4, for thin wall tubes and as shown in Fig. 1 or 2 for thick wall tubes may be used.

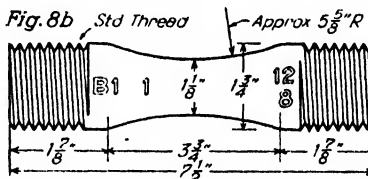
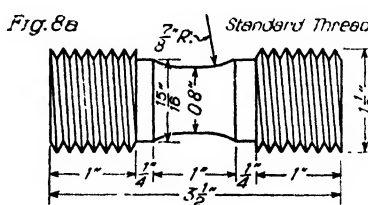
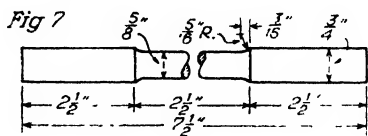


Fig. 7—Tension test specimen for malleable iron (not machined).

Fig. 8—Tension test specimens for cast iron. (a) Machined all over from A.S.T.M. arbitration test bar. (b) Cast to size and only the threads machined on the ends.

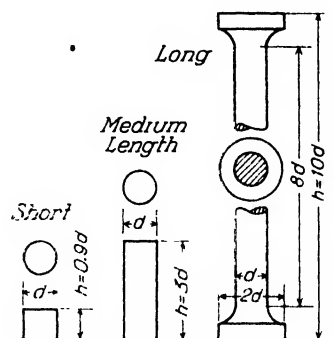


Fig. 9—Compression test specimens for metals.

Other shear tests, in the case of sheet or plate, are made by suitable punches and dies either fitted directly into a testing machine or in a subpress which can be used in a testing machine, so that the load required to shear a specimen of a given size can be measured. The punches and dies are usually circular and the specimen may be any convenient size and shape so as to permit of a complete disk being punched from it. Yet another form of shear test is made by using 3 ring-like dies with either round or square holes through their axes, so that a specimen of the same shape can be inserted, the outer dies supported and the middle die caused to shear a short section from the specimen by suitable fixture in a testing machine. From such a double shear test the shearing strength is readily obtained.

Impact Tests—Tentative standard methods (A.S.T.M.) are now in use for making single blow impact tests of metals. The types and sizes of specimens recommended by the A.S.T.M. are shown in Fig. 10 and 11. A specimen with a "keyhole" notch, as described in the article on "Notched Bar Testing," page 671, is also used. Unnotched $\frac{1}{4}$ in. sq. specimens have been extensively used for checking nonferrous die cast metals.

Many types of impact tests have been experimented with, and numerous sizes and shapes of specimens have been studied in attempting to develop a satisfactory, so-called "shock resistance" test. This investigational work is still in progress, but so far no one type of test or specimen appears to suit all metals, with the

result that many differences obtain in commercial testing practice. In some applications the impact test has shown considerable merit, while in others the results obtained have been of dubious value at best.

Other forms of the impact test include repeated impact and torsion impact tests, each requiring different sizes of specimens, depending on the testing machine used.

Hardness Tests—The hardness tests require no special size or shape of specimens but there are limitations obtaining which are covered in the sections of this book on the various kinds of hardness tests.

Bend Tests—Tentative standard methods are now in use for determining the cold bend properties of metals. The recommended types of specimen for such tests include both a rectangular

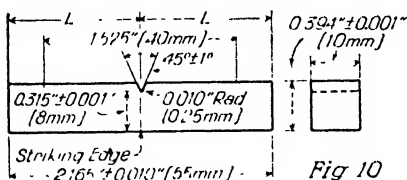


Fig. 10

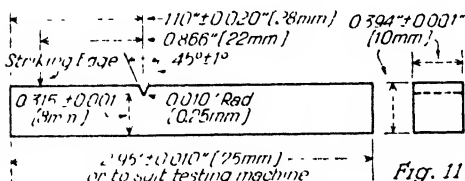


Fig. 11

Fig. 10—Simple beam (Charpy type) impact specimen.

Fig. 11—Cantilever beam (Izod type) impact specimen.

and a round specimen. The rectangular type is the preferred form, with a width at least three times the thickness. The edges of the specimen are required to be smooth, so that the fracture will not take place at the edges. A radius not greater than $\frac{1}{4}$ the thickness of the specimen is permissible on the edges of the specimen. The length of the specimen is permitted to vary with the thickness, but is considered unimportant provided it is sufficient to permit of performing the bending operation. When round bars or specimens are tested by the recommended method, the results obtained should be considered as comparative only; as for any given material the fiber elongation has been found to vary slightly with the diameter of the test piece.

The gage length over which the elongation is to be measured is specified as 0.3 in. in the case of plate from $\frac{1}{4}$ – $\frac{1}{2}$ in. in thickness and 1 in. for all plates over $\frac{1}{2}$ in. in thickness. The gage length should be located at the section of maximum bending, and in the center third of the width of the specimen. A detailed procedure is outlined in the tentative standard methods of the A.S.T.M. for carrying out bend tests using these types of specimens.

Various other types of cold bend tests are used for different types of metal products. In general such tests are made by bending a strip or piece of the metal around a mandrel or die of specified dimensions, by steady application of load or by hammering until rupture occurs or until an angle of either 90° or 180° is attained. Many forms of cold bend attachments are available for commercial

testing machines as well as machines intended solely for the purpose of making bend tests. Although one of the oldest tests and apparently one of the simplest, yet the results obtained are frequently appreciably affected by the procedure and apparatus used in making the tests.

Fatigue Tests—No standard or tentative standard methods including specimen size and shape, have been generally accepted for making fatigue tests of metals. The rotating-beam type of fatigue test is perhaps the one most generally used. In this test the stress in the outermost fibers of the specimen undergoes a cycle of complete reversal from tension to compression, during each revolution of the specimen. Three types and sizes of specimens in current use are given in the Report of the Research Committee on Fatigue of Metals.* There are many other types of fatigue or repeated stress tests used experimentally and in most instances a different size and type of specimen is used. These tests include those in which the stresses are not completely reversed but vary throughout a given range and those involving combinations of tensile, compressive, or torsional stresses.

Cupping Tests—Cupping tests of sheet metals are used as an index of the ductility and in some instances of the drawability of the material. While they have been used for many years, yet at the present time no generally accepted standard conditions of test have been agreed upon, with the result that the values from different types of machines are not concordant. The specimens used in these tests are usually in the form of disks, squares, or strips of suitable dimensions (about 3 in. dia. or width) to fit into the testing machine, and of the same thickness as the sheet metal they represent.

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Load Conversion Table for Testing*

Tons per Sq. In. to Psl.						Kg. Per Sq. Mm. to Psl.					
Tons Per Sq. In.	Psl.	Tons Per Sq. In.	Psl.	Tons Per Sq. In.	Psl.	Kg. Per Sq. Mm.	Psl.	Kg. Per Sq. Mm.	Psl.	Kg. Per Sq. Mm.	Psl.
10.0	22,400	35.0	78,400	70	156,800	10	14,223	60	85,340	110	156,457
10.5	23,520	35.5	79,520	71	159,040	11	15,646	61	86,763	111	157,880
11.0	24,640	36.0	80,640	72	161,280	12	17,068	62	88,185	112	159,302
11.5	25,760	36.5	81,760	73	163,520	13	18,490	63	89,607	113	160,724
12.0	26,880	37.0	82,880	74	165,760	14	19,913	64	91,030	114	162,147
12.5	28,000	37.5	84,000	75	168,000	15	21,335	65	92,452	115	163,569
13.0	29,120	38.0	85,120	76	170,240	16	22,757	66	93,874	116	164,991
13.5	30,240	38.5	86,240	77	172,480	17	24,180	67	95,297	117	166,414
14.0	31,360	39.0	87,360	78	174,720	18	25,602	68	96,719	118	167,836
14.5	32,480	39.5	88,480	79	176,960	19	27,024	69	98,141	119	169,258
15.0	33,600	40.0	89,600	80	179,200	20	28,447	70	99,564	120	170,681
15.5	34,720	40.5	90,720	81	181,440	21	29,869	71	100,986	121	172,103
16.0	35,840	41.0	91,840	82	183,680	22	31,291	72	102,408	122	173,525
16.5	36,960	41.5	92,960	83	185,920	23	32,714	73	103,831	123	174,948
17.0	38,080	42.0	94,080	84	188,160	24	34,136	74	105,253	124	176,370
17.5	39,200	42.5	95,200	85	190,400	25	35,558	75	106,675	125	177,792
18.0	40,320	43.0	96,320	86	192,640	26	36,981	76	108,098	126	179,215
18.5	41,440	43.5	97,440	87	194,880	27	38,403	77	109,520	127	180,637
19.0	42,560	44.0	98,560	88	197,120	28	39,826	78	110,943	128	182,059
19.5	43,680	44.5	99,680	89	199,360	29	41,248	79	112,365	129	183,482
20.0	44,800	45.0	100,800	90	201,600	30	42,670	80	113,787	130	184,904
20.5	45,920	45.5	101,920	91	203,840	31	44,093	81	115,210	131	186,327
21.0	47,040	46.0	103,040	92	206,080	32	45,515	82	116,632	132	187,749
21.5	48,160	46.5	104,160	93	208,320	33	46,937	83	118,054	133	189,171
22.0	49,280	47.0	105,280	94	210,560	34	48,360	84	119,477	134	190,594
22.5	50,400	47.5	106,400	95	212,800	35	49,782	85	120,899	135	192,016
23.0	51,520	48.0	107,520	96	215,040	36	51,204	86	122,321	136	193,438
23.5	52,640	48.5	108,640	97	217,280	37	52,627	87	123,744	137	194,861
24.0	53,760	49.0	109,760	98	219,520	38	54,049	88	125,166	138	196,283
24.5	54,880	49.5	110,880	99	221,760	39	55,471	89	126,588	139	197,705
25.0	56,000	50	112,000	100	224,000	40	56,894	90	128,011	140	199,128
25.5	57,120	51	114,240	101	226,240	41	58,316	91	129,433	141	200,550
26.0	58,240	52	116,480	102	228,480	42	59,738	92	130,855	142	201,972
26.5	59,360	53	118,720	103	230,720	43	61,161	93	132,278	143	203,395
27.0	60,480	54	120,960	104	232,960	44	62,583	94	133,700	144	204,817
27.5	61,600	55	123,200	105	235,200	45	64,005	95	135,122	145	206,239
28.0	62,720	56	125,440	106	237,440	46	65,428	96	136,545	146	207,662
28.5	63,840	57	127,680	107	239,680	47	66,850	97	137,967	147	209,084
29.0	64,960	58	129,920	108	241,920	48	68,272	98	139,389	148	210,506
29.5	66,080	59	132,160	109	244,160	49	69,695	99	140,812	149	211,929
30.0	67,200	60	134,400	110	246,400	50	71,117	100	142,234	150	213,351
30.5	68,320	61	136,640	111	248,640	51	72,539	101	143,656	151	214,773
31.0	69,440	62	138,880	112	250,880	52	73,962	102	145,079	152	216,196
31.5	70,560	63	141,120	113	253,120	53	75,384	103	146,501	153	217,618
32.0	71,680	64	143,360	114	255,360	54	76,806	104	147,923	154	219,040
32.5	72,800	65	145,600	115	257,600	55	78,229	105	149,346	155	220,463
33.0	73,920	66	147,840	116	259,840	56	79,651	106	150,768	156	221,885
33.5	75,040	67	150,080	117	262,080	57	81,073	107	152,190	157	223,307
34.0	76,160	68	152,320	118	264,320	58	82,496	108	153,613	158	224,730
34.5	77,280	69	154,560	119	266,560	59	83,918	109	155,035	159	226,152

*Reprinted from Alloy Steels, published by the Bethlehem Steel Co., Bethlehem, Pa.

Percentage Reduction of Area for Tensile Test Specimens

By Arthur W. F. Green*

Dia.	Area	% R.A.† 0.505 In. Dia.	% R.A. 0.506 In. Dia.	% R.A. 0.504 In. Dia.
0.251	0.0494	75.3	75.4	75.2
0.252	0.0498	75.1	75.2	75.0
0.253	0.0502	74.9	75.0	74.8
0.254	0.0506	74.7	74.8	74.6
0.255	0.0510	74.5	74.6	74.4
0.256	0.0514	74.3	74.4	74.2
0.257	0.0518	74.1	74.2	74.0
0.258	0.0522	73.9	74.0	73.8
0.259	0.0526	73.7	73.8	73.6
0.260	0.0530	73.5	73.6	73.4
0.261	0.0535	73.3	73.4	73.2
0.262	0.0539	73.0	73.2	73.0
0.263	0.0543	72.9	73.0	72.8
0.264	0.0547	72.7	72.8	72.6
0.265	0.0551	72.5	72.6	72.4
0.266	0.0555	72.3	72.4	72.2
0.267	0.0559	71.9	72.2	72.0
0.268	0.0564	71.8	71.9	71.7
0.269	0.0568	71.6	71.7	71.5
0.270	0.0572	71.4	71.5	71.3
0.271	0.0576	71.2	71.3	71.1
0.272	0.0581	71.0	71.1	70.9
0.273	0.0585	70.8	70.9	70.7
0.274	0.0589	70.6	70.7	70.5
0.275	0.0593	70.4	70.5	70.3
0.276	0.0598	70.1	70.2	70.0
0.277	0.0602	69.9	70.0	69.8
0.278	0.0606	69.7	69.9	69.6
0.279	0.0611	69.5	69.6	69.4
0.280	0.0615	69.3	69.4	69.2
0.281	0.0620	69.0	69.2	69.0
0.282	0.0624	68.8	69.0	68.7
0.283	0.0629	68.6	68.7	68.5
0.284	0.0633	68.4	68.5	68.3
0.285	0.0637	68.2	68.3	68.1
0.286	0.0642	67.9	68.1	67.8
0.287	0.0646	67.7	67.9	67.6
0.288	0.0651	67.5	67.6	67.4
0.289	0.0655	67.3	67.4	67.2
0.290	0.0660	67.0	67.2	66.9
0.291	0.0665	66.8	66.9	66.7
0.292	0.0670	66.5	66.7	66.4
0.293	0.0674	66.3	66.5	66.2
0.294	0.0679	66.1	66.2	66.0
0.295	0.0683	65.9	66.0	65.8
0.296	0.0688	65.6	65.8	65.5

†R. A.=Reduction of Area. Dia.=Diameter.

(Continued)

*Metallurgist, Allegheny-Ludium Steel Co., Watervliet, N. Y.

Dia.	Area	% R.A.† 0.505 In. Dia.	% R.A. 0.506 In. Dia.	% R.A. 0.504 In. Dia.
0.297	0.0692	65.4	65.6	65.3
0.298	0.0697	65.2	65.3	65.1
0.299	0.0702	64.9	65.1	64.8
0.300	0.0707	64.7	64.8	64.6
0.301	0.0712	64.4	64.6	64.3
0.302	0.0716	64.2	64.4	64.1
0.303	0.0721	64.0	64.1	63.9
0.304	0.0725	63.8	63.9	63.7
0.305	0.0730	63.5	63.7	63.4
0.306	0.0735	63.3	63.4	63.2
0.307	0.0740	63.0	63.2	62.9
0.308	0.0745	62.8	62.9	62.7
0.309	0.0749	62.6	62.7	62.5
0.310	0.0754	62.3	62.5	62.2
0.311	0.0759	62.1	62.2	62.0
0.312	0.0764	61.8	62.0	61.7
0.313	0.0769	61.6	61.7	61.5
0.314	0.0774	61.3	61.5	61.2
0.315	0.0779	61.1	61.2	61.0
0.316	0.0784	60.8	61.0	60.7
0.317	0.0789	60.6	60.7	60.5
0.318	0.0794	60.3	60.5	60.2
0.319	0.0799	60.1	60.2	60.0
0.320	0.0804	59.8	60.0	59.7
0.321	0.0809	59.6	59.8	59.4
0.322	0.0814	59.4	59.5	59.2
0.323	0.0819	59.1	59.3	58.9
0.324	0.0824	58.8	59.0	58.7
0.325	0.0829	58.6	58.8	58.4
0.326	0.0834	58.3	58.5	58.2
0.327	0.0839	58.1	58.3	57.9
0.328	0.0844	57.8	58.0	57.7
0.329	0.0850	57.5	57.7	57.4
0.330	0.0855	57.3	57.5	57.1
0.331	0.0860	57.0	57.2	56.9
0.332	0.0865	56.8	57.0	56.6
0.333	0.0870	56.5	56.7	56.4
0.334	0.0876	56.2	56.4	56.1
0.335	0.0881	56.0	56.2	55.8
0.336	0.0886	55.7	55.9	55.6
0.337	0.0891	55.5	55.7	55.3
0.338	0.0897	55.2	55.4	55.0
0.339	0.0902	54.9	55.1	54.8
0.340	0.0907	54.7	54.9	54.5
0.341	0.0913	54.4	54.6	54.2
0.342	0.0918	54.1	54.3	54.0
0.343	0.0924	53.8	54.0	53.7
0.344	0.0929	53.6	53.8	53.4
0.345	0.0934	53.3	53.5	53.2
0.346	0.0940	53.0	53.2	52.9
0.347	0.0945	52.8	53.0	52.6
0.348	0.0951	52.5	52.7	52.3
0.349	0.0956	52.2	52.4	52.1

†R. A. = Reduction of Area. Dia. = Diameter.

(Continued)

REDUCTION OF AREA

Dia.	Area	% R.A.† 0.505 In. Dia.	% R.A. 0.506 In. Dia.	% R.A. 0.504 In. Dia.
0.350	0.0962	51.9	52.1	51.8
0.351	0.0967	51.7	51.9	51.5
0.352	0.0973	51.4	51.6	51.2
0.353	0.0978	51.1	51.3	51.0
0.354	0.0984	50.8	51.0	50.7
0.355	0.0989	50.6	50.8	50.4
0.356	0.0995	50.3	50.5	50.1
0.357	0.1000	50.0	50.2	49.9
0.358	0.1006	49.8	50.0	49.6
0.359	0.1012	49.5	49.7	49.3
0.360	0.1017	49.2	49.4	49.0
0.361	0.1023	48.9	49.1	48.7
0.362	0.1029	48.6	48.8	48.4
0.363	0.1034	48.4	48.6	48.2
0.364	0.1040	48.1	48.3	47.9
0.365	0.1046	47.8	48.0	47.6
0.366	0.1052	47.5	47.7	47.3
0.367	0.1057	47.2	47.4	47.0
0.368	0.1063	46.9	47.1	46.7
0.369	0.1069	46.6	46.8	46.4
0.370	0.1075	46.3	46.5	46.1
0.371	0.1081	46.0	46.2	45.8
0.372	0.1086	45.8	46.2	45.6
0.373	0.1092	45.5	45.7	45.3
0.374	0.1098	45.2	45.4	45.0
0.375	0.1104	44.9	45.1	44.5
0.376	0.1110	44.6	44.8	44.4
0.377	0.1116	44.3	44.5	44.1
0.378	0.1122	44.0	44.2	43.8
0.379	0.1128	43.7	43.9	43.5
0.380	0.1134	43.4	43.6	43.2
0.381	0.1140	43.1	43.3	42.9
0.382	0.1146	42.8	43.0	42.6
0.383	0.1152	42.5	42.7	42.3
0.384	0.1158	42.2	42.4	42.0
0.385	0.1164	41.9	42.1	41.7
0.386	0.1170	41.6	41.8	41.4
0.387	0.1176	41.3	41.5	41.1
0.388	0.1182	41.0	41.2	40.8
0.389	0.1188	40.7	40.9	40.5
0.390	0.1194	40.4	40.6	40.2
0.391	0.1200	40.1	40.3	39.9
0.392	0.1206	39.8	40.0	39.6
0.393	0.1213	39.4	39.7	39.2
0.394	0.1219	39.1	39.4	38.9
0.395	0.1225	38.8	39.1	38.6
0.396	0.1231	38.5	38.8	38.3
0.397	0.1237	38.2	38.5	38.0
0.398	0.1244	37.9	38.1	37.6
0.399	0.1250	37.6	37.8	37.3
0.400	0.1256	37.3	37.5	37.0
0.401	0.1262	37.0	37.2	36.7
0.402	0.1269	36.6	36.9	36.4

†R. A. = Reduction of Area. Dia. = Diameter.

(Continued)

Dia.	Area	% R.A.† 0.505 In. Dia.	% R.A. 0.506 In. Dia.	% R.A. 0.504 In. Dia.
0.403	0.1275	36.3	36.6	36.1
0.404	0.1281	36.0	36.3	35.8
0.405	0.1288	35.7	35.9	35.4
0.406	0.1294	35.4	35.6	35.1
0.407	0.1301	35.0	35.3	34.8
0.408	0.1307	34.7	35.0	34.5
0.409	0.1313	34.4	34.7	34.2
0.410	0.1320	34.1	34.3	33.8
0.411	0.1326	33.8	34.0	33.5
0.412	0.1333	33.4	33.7	33.2
0.413	0.1339	33.1	33.4	32.9
0.414	0.1346	32.8	33.0	32.5
0.415	0.1352	32.5	32.8	32.2
0.416	0.1359	32.1	32.4	31.9
0.417	0.1365	31.8	32.1	31.6
0.418	0.1372	31.5	31.7	31.2
0.419	0.1378	31.2	31.4	30.9
0.420	0.1385	30.8	31.1	30.6
0.421	0.1392	30.5	30.7	30.2
0.422	0.1398	30.2	30.4	29.9
0.423	0.1405	29.8	30.1	29.6
0.424	0.1411	29.5	29.8	29.3
0.425	0.1418	29.2	29.5	28.9
0.426	0.1425	28.8	29.1	28.6
0.427	0.1432	28.5	28.8	28.2
0.428	0.1438	28.2	28.5	27.9
0.429	0.1445	27.8	28.1	27.6
0.430	0.1452	27.5	27.8	27.4
0.431	0.1458	27.2	27.5	26.9
0.432	0.1465	26.8	27.1	26.6
0.433	0.1472	26.5	26.8	26.2
0.434	0.1479	26.1	26.4	25.9
0.435	0.1486	25.8	26.1	25.5
0.436	0.1493	25.4	25.7	25.2
0.437	0.1499	25.1	25.4	24.9
0.438	0.1506	24.8	25.1	24.5
0.439	0.1513	24.4	24.7	24.2
0.440	0.1520	24.1	24.4	23.9
0.441	0.1527	23.7	24.0	23.5
0.442	0.1534	23.4	23.7	23.2
0.443	0.1541	23.0	23.3	22.8
0.444	0.1548	22.7	23.0	22.5
0.445	0.1555	22.3	22.6	22.1
0.446	0.1562	22.0	22.3	21.7
0.447	0.1569	21.6	21.9	21.4
0.448	0.1576	21.3	21.6	21.0
0.449	0.1583	20.9	21.2	20.7
0.450	0.1590	20.6	20.9	20.3
0.451	0.1597	20.2	20.5	20.0
0.452	0.1604	19.9	20.2	19.6
0.453	0.1611	19.5	19.9	19.2
0.454	0.1618	19.2	19.5	18.9
0.455	0.1625	18.8	19.2	18.5

†R. A. = Reduction of Area. Dia. = Diameter.

(Continued)

Dia.	Area	% R.A.†	% R.A.	% R.A.
		0.505 In. Dia.	0.506 In. Dia.	0.504 In. Dia.
0.456	0.1633	18.4	18.8	18.1
0.457	0.1640	18.1	18.4	17.8
0.458	0.1647	17.7	18.1	17.4
0.459	0.1654	17.4	17.7	17.1
0.460	0.1661	17.0	17.4	16.7
0.461	0.1669	16.6	17.0	16.3
0.462	0.1676	16.3	16.6	16.0
0.463	0.1683	15.9	16.3	15.6
0.464	0.1690	15.6	15.9	15.3
0.465	0.1698	15.2	15.5	14.9
0.466	0.1705	14.8	15.2	14.5
0.467	0.1712	14.5	14.8	14.2
0.468	0.1720	14.1	14.4	13.8
0.469	0.1727	13.7	14.1	13.4
0.470	0.1734	13.4	13.7	13.1
0.471	0.1742	13.0	13.3	12.7
0.472	0.1749	12.6	13.0	12.3
0.473	0.1757	12.2	12.6	11.9
0.474	0.1764	11.9	12.2	11.6
0.475	0.1772	11.5	11.8	11.2
0.476	0.1779	11.1	11.5	10.8
0.477	0.1787	10.7	11.1	10.4
0.478	0.1794	10.4	10.8	10.1
0.479	0.1802	10.0	10.3	9.7
0.480	0.1809	9.6	10.0	9.3
0.481	0.1817	9.2	9.6	8.9
0.482	0.1824	8.9	9.3	8.6
0.483	0.1832	8.5	8.9	8.2
0.484	0.1839	8.1	8.5	7.8
0.485	0.1847	7.7	8.1	7.4
0.486	0.1855	7.3	7.7	7.0
0.487	0.1862	7.0	7.4	6.7
0.488	0.1870	6.6	7.0	6.3
0.489	0.1878	6.2	6.6	5.9
0.490	0.1885	5.8	6.2	5.5
0.491	0.1893	5.4	5.8	5.1
0.492	0.1901	5.0	5.4	4.7
0.493	0.1908	4.7	5.1	4.4
0.494	0.1916	4.3	4.7	4.0
0.495	0.1924	3.9	4.3	3.6
0.496	0.1932	3.5	3.9	3.2
0.497	0.1940	3.1	3.5	2.8
0.498	0.1947	2.7	3.1	2.4
0.499	0.1955	2.3	2.7	2.0
0.500	0.1963	1.9	2.3	1.6
0.501	0.1971	1.4	1.9	1.2
0.502	0.1979	1.1	1.5	0.8
0.503	0.1987	0.8	1.1	0.4
0.504	0.1995	0.4	0.7	0.0
0.505	0.2002	0.0	0.4	
0.506	0.2010		0.0	

†R. A. = Reduction of Area. Dia. = Diameter.

Fatigue Testing

By R. L. Templin*

For many applications of metallic materials it is necessary to consider not only the static properties of the materials but their resistance to many repetitions of stress as well. The resistance to large numbers of repetitions of stress, or to fatigue, is indicated by means of fatigue tests. Generally, when the fatigue resisting qualities of a material are being considered the property known as the endurance limit is used. Endurance limit is defined as the limiting stress below which the material will withstand without fracture, an indefinitely large number of cycles of completely reversed stress. When cycles of stress other than completely reversed are referred to, suitable qualifying adjectives are used to define the conditions.

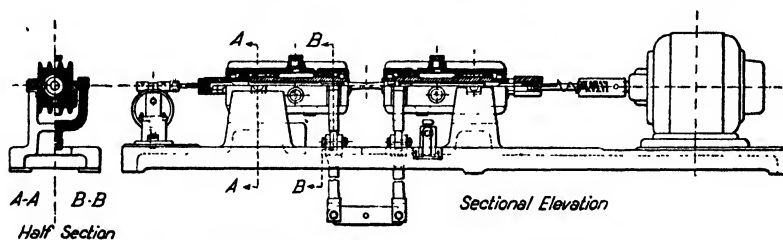


Fig. 1—R. R. Moore rotating-beam fatigue machine.

Values of endurance limit are usually obtained by using a machine of the rotating simple beam type, Fig. 1, in which the outermost fibers of a solid cylindrical specimen are subjected to cycles of completely reversed stress from tension to compression^{1,2}

The specimen used in this machine is shown in Fig. 2. Another machine^a of this general type for testing wire and tubing is shown in Fig. 3. This machine can be used for testing long specimens without machining. Rotating cantilever beam machines of the general type of that shown in Fig. 4 are sometimes used, but the type shown in Fig. 1 is more commonly used than either of the others.

Fatigue specimens usually are less than $\frac{1}{4}$ in. in diameter at the reduced section. Tests of sound uniform ferrous materials, however, using 5 different sizes from 0.05-2.00 in. diameters, have indicated that size of specimen has no effect upon results of fatigue tests.⁴ Size does have some effect in materials which are not sound and homogeneous, such as cast metals containing blowholes.⁵

Because the presence of scratches or tool marks on specimens produces stress concentrations which affect the determination of endurance limit (a rough tool finish reducing it as much as 20% below that for suitably polished specimens²), fatigue specimens must be carefully machined. The machining should be done with sharp tools, using light cuts and slow speeds. Circumferential scratches or tool marks are more injurious than are longitudinal ones. The final finish of the reduced diameter part of the specimen should be such that no circumferential scratches can be seen by the unaided eye. For producing the final finish an abrasive material at least as fine as No. 00 emery cloth is required for steel, and still finer for softer metals.

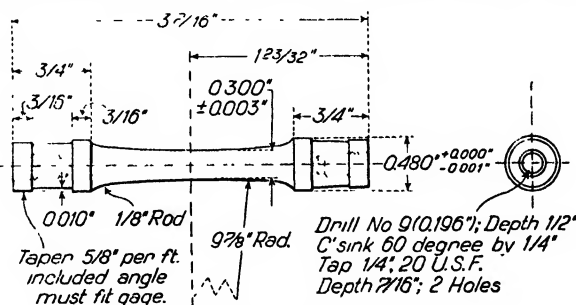


Fig. 2—Specimen for R. R. Moore machine.

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When the test material is of a form which must be used as fabricated (as, for example, sheet or wire), the specimens should be carefully selected and handled to avoid stress concentrations. In such tests the design of the specimen may be such that part or all of the surface at the critical section is the original surface of the material, without any further preparation.^{2, 3} Obviously, any surface imperfections in the original material should be avoided. The sheet specimens used by some investigators have a narrow critical section, making it very important to avoid any damage whatever in handling.⁴

Repeated stress tests require a comparatively long time to determine endurance limits. For this reason recent investigators have been employing machines which can operate at relatively high speeds. Tests have shown that, in tests of sound materials, no appreciable speed effect occurs at speeds up to 10,000 cycles per min., and at speeds of 30,000 cycles per min. only a small increase in endurance limit is obtained.⁵ The design of the testing machine must be such, however, that undesirable effects of secondary stresses are avoided.

The results of fatigue tests are plotted using semilogarithmic coordinates, with values of stress, S , as ordinates and numbers of cycles, N , as abscissas, as shown in Fig. 5.

The semilogarithmic system is used because it is possible to plot on the same diagram both small and large values of N with the same percentage of accuracy, and because there is less danger of an inaccurate selection of the endurance limit than if Cartesian coordinates were used.

For many steels, the S - N diagrams obtained in this way usually consist of two straight lines, one sloping line and one horizontal, joined by a slightly curved "knee," the position of the horizontal line indicating the endurance limit. In such diagrams the "knee" generally occurs at less than 10,000,000 cycles.

For nonferrous metals, the diagram usually is a curve, with the bottom becoming horizontal or nearly so at the endurance limit. A much larger number of cycles is required in order to determine the endurance limit of such metals, some investigators using a 500,000,000-cycle basis for certain materials.

When using endurance limit data, the number of cycles of stress used as a basis for determining this value should be considered and stated in reporting results.⁶ In foreign literature, endurance

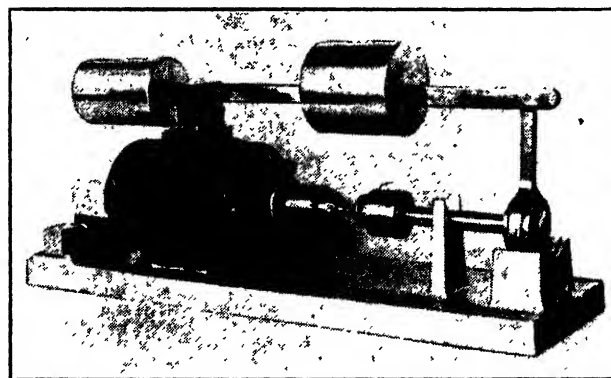


Fig. 4—University of Illinois high speed fatigue machine.

limits of certain metals sometimes are based on 20-50 million cycles. Such values, especially for light alloys, frequently are definitely higher than would be obtained on a 500-million cycle basis.

Because of the time and expense involved in making fatigue tests, various attempts have been made to devise accelerated fatigue tests. Such tests, however,

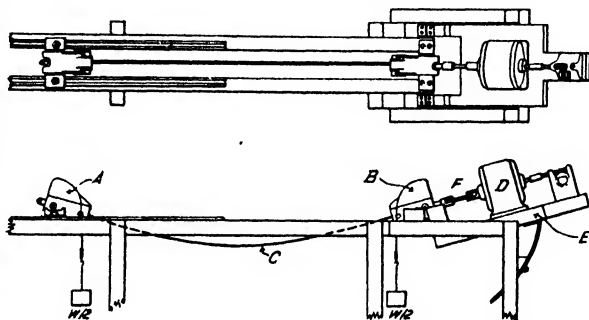


Fig. 3—Shelton wire fatigue machine.

frequently give misleading results. For this reason it generally is advisable to make the regular long time tests.

For many applications, where repeated stresses occur, it is not necessary to know the endurance limit, which has been defined as the maximum stress to

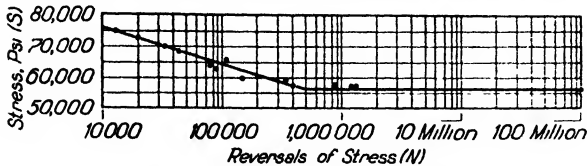


Fig. 5—S-N or stress cycle diagram.

loads may occur only several times daily, and the estimated number of cycles in the life of the bridge may be 25,000. To use an endurance limit based on 500,000,000 cycles, instead of the fatigue strength for 25,000 cycles, would materially affect the design.

Metals are not perfectly homogeneous, but consist of crystals whose planes of cleavage or slip are oriented in many directions. When sufficient stress is applied, slipping occurs on these planes within the individual grains, which at first may not be sufficient to cause any apparent harm. Under alternating stresses sufficient to produce slip, continued repeated slipping, if of sufficient magnitude, causes minute cracks to start to form and to spread, gradually reducing the area of sound metal remaining in any cross section. One of the unsolved problems in the fatigue of metals is the determination of just when and how any harmless slip under repeated stress changes into harmful slip, causing the formation of a destructive spreading fatigue crack. The end of a crack is a point of highly localized stress, so that there is a strong tendency for a crack to grow. The final fracture occurs with practically no distortion or reduction of cross sectional area, and exposes the natural crystalline structure of the material. This appearance of the fracture originally led to the erroneous conclusion that the metal had "crystallized."^{10, 11} It is now known that the fatigue fractures start in the natural cleavage surfaces of the crystals or along crystal boundaries which give the fractures a crystalline appearance. The crystalline appearance is the result of the fracture rather than the cause.

From this explanation of the mechanism of fatigue, it can be realized that "stress-raisers" should be avoided, meaning internal flaws, reentrant angles, abrupt changes in cross section and other factors which tend to cause local increases in stress not considered in ordinary formulas of mechanics.

No precise correlation exists between the endurance limit and any other physical property. Probably yield strength, tensile strength and ductility all have an effect upon the fatigue properties. Perhaps the closest relationship, at least for some metals, exists between endurance limit and tensile strength. Partly for this reason, the endurance ratio, which is the ratio of these two properties, sometimes is quoted.

The structure of a metal appears to have a definite effect upon its endurance properties. Although relatively pure metals usually have lower endurance limits and lower tensile strengths than alloys, their endurance ratios frequently are higher, apparently because of greater uniformity in structure. The endurance ratio is higher for annealed metal than for cold worked or for quenched material, the greater ductility apparently aiding in relieving any stress concentrations which may be present¹² and possibly because annealed materials contain little if any internal strain. Cold working which increases the tensile strength also increases the fatigue strength, but to a less extent. Apparently there is an optimum degree of cold working above which the fatigue strength is decreased by fracturing of the internal structure.¹ Heat treatment may have different effects upon the endurance ratio. In some cases the retention of alloying elements in solid solution raises the endurance limit and the endurance ratio, and in others the formation of intermetallic compounds may produce serious "stress-raiser" effects, depending upon their form and arrangement. Any internal strain produced during heat treatment may seriously harm the fatigue strength. Strain relieving heat treatment usually improves fatigue strength.

Understressing, which consists of subjecting a material to a safe range of alternating stress before subjecting it to a higher range of stress, tends to increase the fatigue strength of the material. In some cases this increase has been found to be as much as 25%.^{13, 14}

which the material may be subjected an indefinitely large number of times. Instead, it is more important to know the fatigue life at various stresses definitely above the endurance limit. An example of such an application is in bridge construction, where maximum

Occasional overloading of a machine part may actually harm the metal. Such oversteering if repeated enough times will reduce the endurance limit.¹ The application of repeated stresses above the endurance limit does not always lower the endurance limit, however, depending upon the number of cycles of this stress. Some investigators have shown the existence of a damage line, which can be defined as separating, in the S-N diagram, the region containing conditions of stress and number of cycles which cause damage from those conditions in which no damage is done.^{12, 14, 15}

Most of this discussion so far has been concerned with completely reversed stresses. There are, of course, many applications where the stresses are not completely reversed but instead vary from one value to another of different magnitude. Such variations of stress may vary from tension to compression, may be all tension or may be all compression. Tests under conditions other than those of completely reversed stress can not be made in the rotating simple beam type of machine but require machines in which the range of stress can be varied between any limits desired. Many machines of this kind have been devised but no one kind has come into general use.¹⁶

For methods of plotting such data, reference should be made to the reports of the Research Committee on Fatigue of Metals of the A.S.T.M.

The effect of corrosion upon fatigue strength, which usually is very important, is discussed in another article in this Handbook.

Some fatigue tests have been made at low temperatures,^{17, 18, 19} and probably a considerably larger number at elevated temperatures.^{20, 21, 22} In general, these tests indicate that most metals have higher endurance limits at temperatures lower than normal room temperature and lower endurance limits at elevated temperatures.

In general, the tests mentioned in the preceding paragraphs use suitably shaped small specimens, and are intended for the determination of the fatigue properties of a material. During recent years, procedures also have been developed for the fatigue testing of fabricated parts and structures, such as riveted joints,²³ aircraft wing beams,²⁴ and boiler shells.²⁵

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Corrosion-Fatigue of Metals

By H. F. Moore*

Corrosion Films on Metals—Under the action of many liquids and gases most metals are corroded. This corrosion takes the form of a film, often only a few molecules thick. This film may give to the metal beneath it a high degree of protection against further corrosion. In that case the film on the metal is usually invisible and it has the power of self healing if cracked. Thicker films, which are characteristic of some metals under the action of a mild corrosive medium, usually do not have this power of self healing, and offer far less protection to the spread of corrosion, especially if the metal is being subjected to repeated stress, causing repeated strain on the film. Even where films do not stop the progress of corrosion they influence the manner in which it proceeds, tending to localize attack at regions under cracks formed under the influence of strain.¹ This localized attack tends to produce pits in the metal, and to render it less able to resist stress on account of the intensification of stress which occurs at any notch or small hole in a piece of metal. The chemical composition of the film depends on that of the metal and on the corroding medium. Oxide films are, perhaps, commonest, but other films, such as phosphate or silicate films are sometimes formed.

Stressless Corrosion and Corrosion Under Steady Stress—If metal is subjected to mild corrosive agents while unstressed, the tendency to form cracks in the oxide film is slight. There is relatively little tendency to form pits, at least in structural steels, and the static strength of the metal is diminished but slightly.² Such corrosion is called "stressless corrosion."

If steel with a thin layer of oxide on it is subjected to a steady load, the thin film of oxide may be cracked at various points, with resulting increased localized corrosion through the cracks. Such intensified corrosion is shown by the "Luders lines" often seen on unpainted structural steel which has been bent or stretched cold,³ causing heavy stress and strain at the bend, and a consequent strain on the film which caused it to crack. However, if the load remains steady, the cracks in the film will tend to heal themselves and the further progress of corrosion will be retarded and perhaps almost entirely stopped.

Damage Under Stressless Corrosion—A metal surface which has been subjected to stressless corrosion, or which is subjected to a combination of steady stress and corrosion, has its resistance to damage under further steady load reduced somewhat, and its resistance to fatigue failure more seriously reduced. However, this damage is far less than the reduction in resistance to repeated stress which is caused by the simultaneous action of repeated stress and corrosion. In any case the damage is due to the "stress raisers"—the microscopic notches formed in the surface of the metal by corrosion. The effect of notches of all kinds in steel has long been recognized as a major factor in causing fatigue fracture of metals, and the magnitude of the effect produced depends upon sharpness of notch, depth of notch, slope of walls of notch, and whether the notch is produced by cutting, by chemical action or by indentation with a blunt tool. Corrosion seems to produce a distinctly destructive type of notch, but stressless corrosion at least under mild corrosive agents does not often produce deep notches.

R. R. Moore's⁴ experiments on S.A.E. 1045 steel corroded without stress by salt spray showed a reduction of fatigue strength (measured by the endurance limit) due to corrosion of 22%. His experiments on duralumin showed a reduction of endurance limit of about 35% after stressless corrosion.

Simultaneous Corrosion and Repeated Stress; Corrosion-Fatigue—If a metal is subjected to a corrosive medium while also being subjected to cycles of repeated stress, the protective film may be repeatedly broken. For steel, corrosion spreads through cracks and forms relatively deep pits which act as stress raisers, and greatly reduce the fatigue strength of the metal. Practically all the known metals of construction are subject to this action under repeated stress which is known as corrosion-fatigue. How rapidly the destructive effect progresses depends upon: (1) the rapidity of formation of cracks in the film compared with the rapidity with which the protective film can be repaired; (2) the relative porosity of rapidly healed and slowly healed films; (3) the influences which tend to produce a wide spread distribution of electrochemical couples over the surface of metal, and hence relatively uni-

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form corrosion. The corrosion-inhibiting power of colloidal clay in "drilling mud" in oil wells is an example.

The above is a statement of what is now regarded as the principal cause of corrosion-fatigue. There are many phenomena such as the change of electric potentials within the metal due to stress conditions, and the tendency of the products of corrosion to clog up the pits and, perhaps, delay the further spread of corrosion. Usually the prime cause of the damage is corrosion, but the immediate cause of failure is the "stress raiser" effect of the pits.¹

Fatigue Strength of Metals Under Corrosion-Fatigue—The first published account of laboratory experiments on corrosion-fatigue is that of Haigh,¹¹ who made fatigue experiments on brasses while subjected to chemical attack and who later took a prominent part in the study of the effect of sea water in reducing the life of tow ropes for vessels.

In 1925, D. J. McAdam, Jr. began a very extensive experimental study of corrosion-fatigue.¹² His results, and the results of other experimenters have developed the fact that under so mild a corrosive agent as relatively pure water the fatigue limit may be reduced much below that in air. In fact, no definite value for fatigue limit for indefinitely long life under corrosion-fatigue has been found.¹³ In case of corrosion-fatigue limits, it is important to state the limiting number of cycles which were used in the test, and also the frequency of cycles of stress. In noncorrosive fatigue tests the number of cycles of stress is of prime importance, and, within wide limits, the frequency of cycles of stress is of minor importance. In corrosion fatigue tests the time under corrosive action is also of importance. If the frequency of cycles of stress is low, then for a given number of cycles there elapses a relatively long time during which corrosion can get in its destructive work. Hence the endurance limit is lowered. The experiments of McAdam and others showed, with the exception of the stainless steel group, the corrosion-fatigue limit of heat treated alloy steels (based on 10-100 million cycles of stress) is but little if any above the corresponding corrosion-fatigue limit of ordinary low and medium carbon steels. The stainless steel group resists simultaneous corrosive attack and repeated stress distinctly better than do either plain carbon steels or heat treated alloy steels. With nonferrous metals, the effect of corrosion-fatigue is so varied that no general statement can be made.

Values for Corrosion-Fatigue Endurance Limits—Table I is a graphical representation of average value of fatigue limits in air and fatigue limits under a stream of tap water for several groups of metals. Each value is the average of results from a number of reported tests. This table would not be of a high degree of accuracy for predicting the behavior under corrosion-fatigue of any given metal, but does give an idea of the relative effects of corrosion-fatigue for the main classes of structural metals in tap water. A different corroding medium (salt water) might change materially the relative fatigue strength of the metals listed.

The corrosion-fatigue limits for the heat treated alloy steels do not seem to be any higher than those for the ordinary low and medium carbon steels. This is in harmony with the increased sensitivity of high strength steel to notches and other localized "stress raisers."

For a larger number of cycles of stress as given in Table I or for cycles of stress occurring less frequently, the limits would be distinctly less. In his summary Gough¹⁴ makes use of the terms, suggested by McAdam, "total damage" and "net damage." "Total damage" is the percentage reduction from the fatigue limit determined in air to the fatigue limit found when specimens have been subjected to some definite routine of corrosion-fatigue. The "net damage" is the percentage reduction from the fatigue limit of metal subjected to some definite period of "stressless corrosion" to the fatigue limit of specimens which have been subjected to some definite routine of corrosion-fatigue.

From McAdam's data the following tentative relation between stress range and average rate of net damage is given.

$$R = CS^n$$

In which R = rate of net damage in % per day.
 S = stress range in psi.
 C and n are experimental constants.

Gough quotes from McAdam's results values of n varying from 2.6 to 5.7.

Gough¹⁴ notes the report from German investigators that there seems to be some degree of correlation between notch-sensitiveness of a metal and its resistance to corrosion-fatigue.

Table I
Characteristic Results of Corrosion-Fatigue Tests
 Based largely on the work of D. J. McAdam, Jr.

Endurance limits reported are for 20,000,000 cycles of stress. Speed of testing, 1450 cycles per minute. Tests made in rotating cantilever-beam fatigue machines.

Metal	Approximate Composition, %	Tensile Strength, Psi.	Endurance Limit in Air, Psi.	Endurance Limit in Stream of Water,* Psi	Reduction of Endurance Limit by Corrosion-Fatigue, %
Plain Carbon Steels					
Armco iron, as rolled.....	0.02 C	44,000	24,000	20,000	16.7
" " annealed.....	0.02 C	43,000	22,000	15,000	31.8
Low carbon, as rolled.....	0.14 C + .098 Cu	84,000	43,000	18,000	62.8
" " annealed.....	0.14 C + .098 Cu	81,000	32,000	20,000	37.5
Low carbon, as rolled.....	0.15 C	64,000	34,000	20,000	41.2
" " annealed.....	0.15 C	52,000	25,000	16,000	36.0
Medium carbon, as rolled.	0.26 C	84,800	36,000	15,000	58.3
" " annealed.....	0.26 C	59,000	24,000	15,000	37.3
Medium carbon, Ht. treated	0.35 C	104,000	52,000	19,000	63.5
" " annealed..	0.35 C	79,000	33,000	23,000	30.4
Medium carbon, Ht. treated	0.49 C	110,000	53,000	19,000	64.2
" " annealed..	0.49 C	82,000	33,000	21,000	63.6
Medium carbon, Ht. treated	0.56 C	112,000	54,000	16,000	70.4
" " annealed..	0.56 C	90,000	42,000	19,000	54.8
Alloy Steels—Heat Treated					
Nickel steel.....	S.A.E. 2320	124,000	69,000	24,000	65.2
Chromium-nickel steel.....	S.A.E. 3312	130,000	61,000	21,000	65.6
Chromium-vanadium steel.	S.A.E. 6140	179,000	78,000	16,000	79.5
Chromium-molybdenum steel	S.A.E. 4130	118,000	57,000	20,000	65.0
Nickel-silicon steel.....	3.0 Ni, 1.5 Si	251,000	108,000	13,000	88.0
Corrosion Resisting (Stainless) Steels—Annealed					
"18-8"	18.0 Cr, 8 Ni	125,000	52,000	49,000	5.9
Chromium-nickel steel.....	5.0 Cr, 23.0 Ni	98,000	50,000	31,000	38.0
Stainless iron	14.0 Cr, 0.08 C	90,000	49,000	31,000	36.8
Stainless steel.....	13.0 Cr, 0.33 C	97,000	51,000	35,000	31.4
Chromium steel	27.0 Cr, 0.20 C	81,000	44,000	40,000	9.2
Nonferrous Metals					
Monel metal, as fabricated	68.0 Ni, 29.0 Cu	128,000	51,000	26,000	49.1
" " annealed....	68.0 Ni, 29.0 Cu	81,000	36,000	26,000	27.8
Copper, cold drawn.....	100.0 Cu	47,000	18,000	18,000	0
" " annealed.....	100.0 Cu	31,000	9,000	10,000	-11.1**
Nickel, as fabricated.....	100.0 Ni	132,000	50,000	26,000	48.0
" " annealed	100.0 Ni	78,000	33,000	23,000	30.3
Brass, as fabricated.....	60.0 Cu, 40.0 Zn	84,000	24,000	18,000	25.0
" " annealed.....	60.0 Cu, 40.0 Zn	53,000	21,000	18,000	14.3
Aluminum, as fabricated..	100.0 Al	16,000	7,500	2,500	66.7
Duralumin, as fabricated.	95.0 Al, 4.0 Cu	69,000	18,000	8,000	55.6
" " annealed.....	95.0 Al, 4.0 Cu	33,000	13,000	7,500	42.3

*Tested under a stream of fresh water. A fairly representative analysis of the water showed the following composition, values in parts per million: Silica, 11.7; iron and aluminum oxides, none detected; calcium sulphate, 1.89; calcium carbonate, 200; magnesium chloride, 17.3; sodium chloride, 140; sodium sulphate, none detected. This is a rather hard water.

**Increase in endurance limit.

In Gough's⁷ paper the effect of time on corrosion-fatigue is summarized by the conclusion from test results that at low frequencies of stress-cycles the rate of net damage is nearly proportional to the frequency; at high frequencies of stress-cycles the rate of net damage is nearly independent of the frequency.

Few data are available on corrosion-fatigue under cycles of stress other than those involving complete reversal. At the University of Illinois a few corrosion-fatigue tests of structural steel under cycles of flexural stress varying from zero to a maximum gave percentage reductions of the fatigue strength in air of the order of magnitude of the percentages found under cycles of reversed stress.

Gough and Sopwith⁸ have recently reported extensive tests on the influence of range of stress on the resistance of metals to corrosion-fatigue. The corroding

medium used in their tests was a 3% salt spray. They report that for most of the metals tested the effect of variation of ratio of minimum to maximum stress during a cycle (variation from one-direction repeated stress to reversed stress) was about the same under salt spray as was the effect on the fatigue strength in air.

Corrosion-Fatigue in Different Corrosive Media—A general rule cannot be given for the effect of different corrosive media. Perhaps the most nearly general statement possible is that any corrosive medium under which the localization of corrosive attack is determined largely by stress conditions will, if allowed sufficient time, start a spreading fatigue crack. Specimens tested in a free stream of liquid, or in a stream of liquid saturated with air, show greater damage by corrosion-fatigue than do specimens tested in a quiet bath of liquid, especially in a bath free from dissolved air. Distilled water, applied in a stream, causes corrosion-fatigue damage, and for some steels seems as detrimental as ordinary tap water. Acids and alkaline solutions produce various effects. Thum and Holz²⁵ report that strong solutions of soda lyes drastically reduced the fatigue strength of boiler steels, while weak solutions slightly increased the fatigue strength. Some metals which show a good resistance to stressless corrosion show poor resistance to corrosion-fatigue. Again it may be emphasized that the toughness of the protective film on the metal is the main factor in determining resistance to corrosion-fatigue.

Table II
Results of Fatigue Tests in Air and in a Partial Vacuum

Metal	Approx. Composition, %	Condition when Tested	Tensile Strength, Psi.	Endurance Limit Reversed Tension-Compression		
				In Air (A), Psi.	In Vacuum ^a (B), Psi.	Ratio (A) (B)
Armco iron	0.02 Cu, 0.03 Mn	Normalized	49,500	28,900	29,400	0.984
		Annealed	.....	24,000	24,400	0.984
Mild steel	0.13 C	Hot rolled	62,800	29,100	30,700	0.949
Medium steel.....	0.50 C	Cold rolled	141,500	48,700	50,400	0.965
Noncorroding steels....	15.0 Cr, 0.12 C	Hard. and Tempered	97,000	49,300	49,900	0.990
	17.0 Cr, 1.2 Ni, 0.25 C	Hard. and Tempered	122,000	63,300	63,300	1.000
	18.0 Cr, 8.0 Ni, 0.10 C	Cold rolled	148,500	55,600	54,400	1.022
Chromium-nickel steel.	3.4 Ni, 0.6 Cr, 0.36 C	Hard. and Tempered	201,500	79,500	81,800	0.973
Duralumin	4.25 Cu, 0.64Mg, 0.82 Fe	Rolled	62,700	17,600	18,500	0.953
Magnesium alloy	2.46 Al	Rolled	35,800	12,600	12,600	1.000
Copper	99.96 Cu, 0.04 O ₂	Annealed	32,200	9,650 ^b	10,950 ^b	0.881
	99.92 Cu, 0.04 O ₂	Extruded	31,600	10,100 ^b	10,500 ^b	0.962
	99.96 Cu, "oxygen free"	Extruded	32,000	9,650 ^b	10,300 ^b	0.937
Brass	69.85 Cu, 30.11 Zn	Annealed	44,300	16,100	20,400	0.790
Copper-nickel alloy	78.92 Cu, 20.61 Ni	Annealed	50,400	18,100	18,100	1.000
Lead	99.99 Pb.	Extruded	.....^c	380 ^b	850 ^b	0.447

^aPressure in vacuum approximately 0.0008 mm. of mercury.

^bEndurance diagram did not become definitely asymptotic to a stress value. Endurance limit determined for 30 million cycles of stress.

^cTensile strength of lead depends on time under load.

Corrosion in Air—Probably air has a slight corrosion-fatigue effect on most metals although for the steels this effect seems to be quite small. Table II compiled from data by Gough and Sopwith⁸ shows some effects of air corrosion. As compared with the fatigue strength in air the fatigue strength of lead tested in a partial vacuum shows a marked proportional improvement. The stress-cycle diagrams for some aluminum alloys tested in air do not show definite endurance limits even after 500,000,000 cycles of stress, but continue to have a downward slope quite like the stress-cycle diagram of some metals under corrosion-fatigue. In the cases of those metals which do not show a clearly marked endurance limit in air, an investigation of possible corrosion-fatigue in air would be valuable. The tests of Gough and Sopwith show that the main corrosive factor in air is a combination of oxygen and water vapor.

Protection Against Corrosion-Fatigue—Protective Coatings—Since corrosion-fatigue may reduce greatly the fatigue strength of metals the question of protection against this is of major importance. Protection against corrosion-fatigue should be a major factor in the design of structural and machine members. Protective coatings

may offer a greater or less degree of protection against fatigue. A heavy coating of grease has been shown by laboratory experiments¹⁸ to offer a fair degree of protection. A coating of rubber cement²⁰ or a tight fitting rubber sheath²⁴ has been found to give considerable protection. Under salt spray, zinc plating on duralumin afforded an effective degree of protection,⁴ distinctly better than a coat of pure aluminum sprayed on. With the same metal, coatings of organic resins and enamels gave a good degree of protection especially if the material had been anodized.

Naturally noncorrosive metallic coatings suggest themselves as protectives of corrosion-fatigue. Fuller² found that chromium plating was quite effective on steel exposed to steam. Harvey¹² has made a rather extensive study of zinc as a protective coating against corrosion of steel. He studied hot galvanizing, sherardizing, and electroplating as means of applying the zinc coating. His results show that for uncoated specimens of a steel with about 100,000 psi. tensile strength, the reduction of endurance limit (10,000,000 cycles of stress) of a steel with an in-air endurance limit of 60,500 psi. was 66% under a stream of tap water. For galvanized and sherardized specimens the reduction was about 33%. For electroplated specimens there was no reduction. It seems well to note that the electroplated specimens were not pickled but were merely degreased by alcohol and ether. Harvey holds that all the coatings prevented the contact of water with steel. Microscopic analysis showed that for the galvanized and sherardized steel there existed a layer of intermetallic compounds of alloys some of which were probably very brittle, and Harvey suggests that cracks starting in this brittle region and spreading into the steel were the cause of lower fatigue strength. Gerard and Sutton⁴ also found that electroplating with zinc was effective in reducing corrosion-fatigue damage to duralumin. Nitriding steel has been used to give it a definite resistance to corrosion-fatigue. In some specimens of nitrided steel under corrosion,¹⁵ fatigue failure started in the core of the specimen and afterward the nitrided case peeled off.

Recent tests have been reported by Sopwith and Gough.²² They state that the essential requirements for protective coatings against corrosion-fatigue are: (1) The coating must adhere firmly to the base metal. (2) Either it must be anodic to the steel base or it must be continuous and nonporous. In practice it is difficult to secure and maintain continuous, nonporous coatings, hence it is preferable that the coating should be anodic to the steel base. Then it will afford some protection even when its continuity is broken. (3) Its mechanical properties must not be such as to reduce fatigue resistance in air. If it is not sufficiently adherent to be able to transmit cracks to the steel, the coating itself must not crack at too low a stress and thus render the protection purely anodic at an early stage.

Sopwith and Gough found that under a 3% salt spray a satisfactory degree of protection was afforded by galvanizing, sherardizing, and sprayed aluminum plus enamel. A fair degree of protection was afforded by zinc plating, cadmium plating, and sprayed aluminum. A phosphate coating plus enamel and an enamel coat alone gave some protection but were not nearly so effective as the metallic coatings. Enamel was found to improve the protection given by sprayed aluminum, but both enamel and oil reduced the protection given by cadmium plating.

Protection Against Corrosion Fatigue by Rolling the Surface—Tests in Germany²⁸ showed that resistance of certain steels to corrosion-fatigue was somewhat increased by cold working the surface. The cold working seemed to "smooth out" the minute projections and notches in the surface and to offer less area for corrosive attack. Matthew¹⁹ indicated that simultaneous corrosion and abrasion of steel showed a tendency to a mutual inhibition of destructive effects. This was explained by the reduction of the grinding action of abrasion which became a polishing action under the lubricating effect of the corrosive liquid.

Chemical Inhibitors of Corrosion-Fatigue—In some cases, for example, oil well pipes and sucker rods, it is possible to add chemicals to the corroding medium which will partly or wholly inhibit its damaging action. Dilute solutions of trisodium phosphate¹⁴, ²⁸ and sodium carbonate¹⁰ have been found to have some retarding effect on corrosion-fatigue damage in steel. Tests showing effective chemical inhibition of corrosion-fatigue damage have been made by Speller, McCorkle, and Mumma.²⁴ They used sodium dichromate (a strong oxidizing agent) in the water sprayed on the specimens, and found that it was an almost perfect "inhibitor" of damage due to corrosion-fatigue. This is probably due to the fact that the strong oxidizing action of the sodium dichromate built up protective film so rapidly that cracks were not formed, or at least never penetrated to the surface of the metal under the protective film. This research also emphasized the importance of small local dif-

ferences of surface condition, the effect of which may be far more destructive than the effect of the general environment.

Corrosion-Fatigue of Welds—Welds in structural steel do not seem to show any great difference in resistance to corrosion from that of the parent metal. Corrosion fatigue results¹² have been determined for stainless steel and for resistance and gas welds. The gas weld was anodic to the base metal while the resistance weld was cathodic. Heat treatment which dissolved carbides increased the resistance to corrosion-fatigue. In general, there seems no evidence that welded joints are more susceptible to damage by corrosion-fatigue than is the base metal welded.

Cumulative Effect of "Stress Raiser" and Corrosion-Fatigue—Dolan¹ has carried out tests under reversed torsion on standard fatigue specimens, specimens with sharp fillets and specimens with holes. Tests were made in air and under a stream of tap water. Low carbon steel and heat treated S.A.E. 3140 steel were tested. The damaging effect of combined corrosion-fatigue and a stress raiser were decidedly greater than the effect of either alone for the S.A.E. 3140 steel, especially for the specimens with holes. For the low carbon steel the damaging effect of combined corrosion-fatigue and a stress raiser was but slightly larger than that for corrosion alone. Later tests of heat treated S.A.E. 3140 steel and several low alloy steels under reversed flexure yielded similar results.

Corrosion-Fatigue and Caustic Embrittlement—In connection with steel pressure vessels an interesting phenomenon is that known as "caustic embrittlement." Under steady, high stresses and in the presence of a strong alkaline solution intercrystalline cracks have developed both in vessels in service and in specimens under laboratory tests. It seems probable that the chemical action which starts these cracks is due to the presence of small quantities of impurities in the solutions used, and silicates seem to be indicated as impurities. The phenomena of corrosion-fatigue seem to be distinctly different from those of caustic embrittlement. The corrosion-fatigue cracks when started in steels and most of the nonferrous metals spread within the crystals just as fatigue cracks spread when tested in air. Unpublished results by Betty at the University of Illinois show that under the corrosive influence of water which had been chemically treated so as to prevent caustic embrittlement, corrosion-fatigue took place in boiler steel.

Corrosion-Fatigue Failures in Service—Corrosion-fatigue failures have occurred in marine propeller shafts, ship's rudder main piece; steering hubs and stub axles of automobiles; boiler and superheater tubes; turbine rotors, discs, and blading; street car and locomotive springs; piping conveying corrosive liquids; wire of airplane frames; pump shafts; pump rods; pump bodies; watercooled piston rods of Diesel engines; and steel railway sleepers. Gough¹ feels that the occurrence of corrosion-fatigue in marine boiler plates has not yet been definitely proven, differing in this opinion from McAdam. In the service failures studied the exposed surfaces have in some cases suffered appreciable damage by general corrosion, but the reduction of dimensions by corrosion is quite insufficient to explain the great reduction of strength. Corrosion-fatigue depends on localized action.

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Simple Statistical Methods as a Guide in Control of Operations and of Quality of Product*

In any single manufacturing operation whatever there is bound to be some lack of complete uniformity which may affect the usefulness of the product. In a sequence of operations the likelihood of significant variation of the final product is much greater, as the maximum deviation from the mean in the final product is usually the sum of the maximum deviations from the mean in each step in the sequence of operations. Thus it is inevitable that there will be some variation between the units of any metal product no matter how carefully each of the many steps in its manufacture has been carried out; and, in general, such difficulties as there are arise from those units which differ most widely from the average quality as specified. For, to the user, extra good units do not make up for poor units; what he wants, especially in these days of automatic operations, is a product no unit of which falls outside certain limits, and the limits which he is willing to tolerate are becoming always closer. We are therefore forced to consider the extent and frequency of departure from the average, or the mode of distribution of the several cases about the average; and this implies that if we are to treat these matters intelligently we must have recourse to statistical methods.

Conclusions deduced from statistics have not always commanded universal assent, but experience with the application of statistical methods to metallurgical and manufacturing operations which are reasonably well controlled, has demonstrated their usefulness and reliability, when properly used and interpreted. By their use it is possible to differentiate variation which is inherent in a given process from variation due to some abnormality in that process. Methods are available which enable us to decide, from the variation in test results of selected samples, in how far the quality of the individual units is being maintained within the requisite limits, or to foretell the probability of performance even where only limited data are available. They also serve to bring out relationships between actual variables in a process even where there is no functional relationship between these variables. They suggest moreover that in some specifications, rigid limits—for instance, of composition or of quality—could, with advantage to all concerned, be replaced by the requirement that a stated high percentage of the material should be within the stated limits.

The statistical methods most frequently employed involve the use of frequency distributions, cumulative distributions, control charts, correlations, and significance tests. It is manifestly impossible, in the space available, to discuss all of these methods in such a way that a reader, previously unacquainted with them, could apply them; and their seeming complexity might indeed discourage him from trying them. We are therefore limiting ourselves to an outline of a simple case—the construction and use of frequency curves—which involves little mathematics; and in the appended references we refer the reader who becomes interested in going further, to a number of pamphlets and books which set forth more mathematical methods of statistical analysis and discuss the whole subject broadly. It may be added that most of these methods are less difficult than they may seem at first sight; when once set up they may be used and applied by a person without special aptitude for mathematics, provided always that one uses common sense in arranging the observations and in interpreting the results.

The frequency curve represents the frequency of occurrence of the several values, or mode of distribution of the value, of a single variable X for a large group of units or batches of the product. Its useful interpretation is based on the presumption that the group is large enough to permit us to consider the variation of X as being unaffected by the variation of whatever other factors may influence the quality or fitness of the product for its intended use. The merit of frequency curves is that they enable us to analyze, factor by factor, complex situations in which a large number of possible variable factors are concerned, without bringing in any personal bias; this enters only when we begin to seek the causes to which the variation in product is to be attributed.

*This was written by John Johnston, with the aid and advice of J. E. Gould, National Tube Co., Lorain Works, Anson Hayes, American Rolling Mill Co., and W. A. Shewhart, Bell Telephone Laboratories. It is presented as a simple introduction to the subject, designed to arouse interest on the part of those still unacquainted with this valuable tool.

To illustrate the method of drawing and using a frequency curve, it is best to consider a specific example. For this we shall take a large group of heats of steel, considering as the variable X the casting temperature, which ranged from about 2700 to 2950°F. The difference is the total range required on the horizontal axis. This range we divide into equal intervals, or unit cells, each representing in this case an interval of 20°. This interval was chosen because the accuracy of measurement is of this order, and there is no point in making the interval smaller than the probable accuracy of the data under consideration. The choice of size of unit cell does not affect the curve materially if the number of cases (heats) is large enough and if the number of intervals is not too small; it is a matter of judgment, governed largely by the degree of accuracy of the data and the size of the group of cases available. If the interval is too small, there will be, with a limited number in the group, too small a number in each and the curve will be irregular and show details which may well be without significance; if the interval is too wide, the significant details may be masked. In general it is preferable to have a dozen cells if the accuracy of the data and the variation of X make this possible. Having decided on the size of the interval, we examine the records for the group, and count the number of cases in which X falls within each of the several intervals or cells. When the whole group has been counted in this way, the number in each group is reduced to a percentage of the whole, and this percentage is plotted as ordinate at the center of each cell on the horizontal scale. These points are connected by straight lines as in Fig. 1; or vertical blocks or bars may be used to show the relative number within each interval of the variable. The resulting frequency distribution is usually not quite smooth, but is smoother the larger the group; consequently little significance is to be attached to small irregularities, particularly when the group is small.

It is to be noted

that each frequency distribution deals with a single variable only, the other co-ordinate being merely a number. Consequently there is a separate curve for each variable considered, without reference to the other possible variable factors. We may, however, use as the variable the sum or product or quotient of two recorded variables, as derived separately for each case in the group; but a combination of variables should

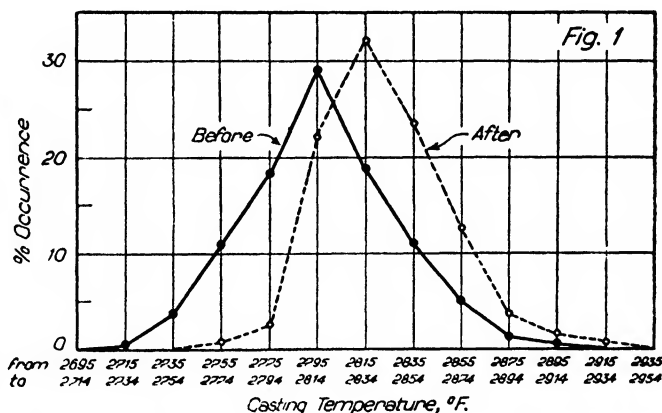


Fig. 1—Typical frequency curve; casting temperature of a large group of heats before, and after, a change in practice.

in general be tried only if there is a specific reason for doing so. A single diagram should be concerned with only one variable, but it is highly desirable to draw on the same sheet the corresponding diagram for groups to be compared. Such a comparison may be made on similar groups of heats made at different periods (for instance, before and after some change in practice) or in different mills, or of "good" with "bad" heats as separated by any criterion of quality that may be available (for instance, hardness or ductility). Such a comparison is illustrated in Fig. 1. We may also arrange a large group in order of increasing Y , where Y is a second variable (that is, manganese or sulphur content), divide into three (or four) equal subgroups, and then compare the frequency distribution of the variable X for the highest and for the lowest of these subgroups; this shows at once how far the distribution of the values of X is affected by the factor Y .

The frequency curve for the variable X shows at a glance, for the group of cases included in the diagram: (1) the total range of X ; (2) the total number of cases falling within, or without, any specified limits of X ; (3) the most frequent

value of X ; (4) the general symmetry of the distribution of the values of X about the peak. Obviously a high narrow curve corresponds to a close control of the factor X ; a low broad curve indicates inadequate control. Yet the average value of X may readily be the same for both of the distributions just named, or indeed for any number of different modes of distribution; this shows that averages have little significance unless the shape of the distribution of the values averaged is substantially identical in all the groups compared. Thus in comparing similar groups of product made at different periods or in different ways or in different places, we may have the same average value of X yet with better or worse control of its variation as indicated by a narrower or broader loop respectively.

In general, the outstanding advantage of a frequency curve is that it depicts characteristics of the distribution of the values of one variable at a time for a group of cases, and that it is based on no assumptions other than that the number in the group is large enough to insure that the distribution of all other variable factors is accidental and so without specific directive effect upon the single variable considered. This implies that the data have been grouped rationally, based upon a fundamental knowledge of the process in question; in other words, that the group considered does not comprise two (or more) subgroups which are known to differ specifically from one another with respect to some factor. The method is applicable to any factor which can be obtained repeatedly as a numerical quantity; from residual carbon to temperature at any step in the process of manufacture, from cost or overall recovery of product to tensile strength of similar samples or diameter of similar wires. It furnishes what may be called a statistical aspect of quality with respect to any given step of a process or any given property of a product; but being by definition statistical does not of itself indicate the why or wherefore of any differences it may reveal. Nevertheless, if on comparison of two similar groups, one of "good," the other of "bad" product, we find the two frequency curves for any given variable to be substantially identical, we can conclude with some confidence that this particular variable is substantially without influence upon the "goodness" of the product as indicated by the criterion which was used; moreover if the pairs of curves for each of the variables observed are substantially identical, we should look for some other factor which might influence the "goodness" or "badness" of the product, or inquire into the significance of the criterion used to distinguish "good" from "bad."

If the variation of X is believed to be random, then the cumulative curve, derived from a comparatively large group, may advantageously be used to forecast the per cent of occurrences which will fall within any specified limits. The following table illustrates how such a curve may be readily prepared:

Interval of " X "	% of All Observations	Cumulative % of Observations
52-54	1.0	1.0
55-57	2.5	3.5
58-60	4.0	7.5
61-63	12.0	19.5
64-66	16.0	35.5
67-69	19.5	55.0
70-72	19.0	74.0
73-75	15.0	89.0
76-78	8.0	97.0
79-81	2.0	99.0
82-84	1.0	100.0
Total	100.0	

Such a cumulative curve may be plotted satisfactorily on arithmetic probability graph paper.

One of the recent developments in statistical technique of particular usefulness in detecting assignable or findable causes of variability in the properties of metals during production is the statistical quality control chart. A recent paper by Chancellor briefly illustrates some of the uses of this technique in the steel plant. By means of an analysis of a series of comparatively small samples taken in the order of the production of the material, it is often possible to detect the presence of

causes of variability which should, from an economic viewpoint, be removed from the process. As an example, Fig. 2 shows a control chart for chipping time taken from this paper, in which the average for successive small groups of samples is plotted. When this average falls outside the appropriate limits, it is usually possible to find and remove the cause, thus reducing the variability. Two such kinds of causes were found in this case, as is indicated in the figure. The use of such techniques leads to many economies, examples of which will be found in the literature cited below.

It would lead too far to give a complete discussion of the application of these methods; for this the reader is referred to the books and pamphlets noted below which treat and illustrate the several methods in the requisite detail.

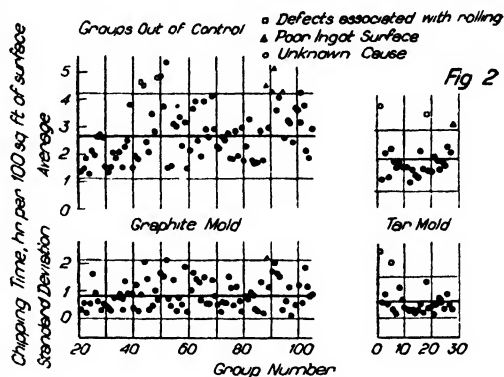


Fig. 2—Control chart for chipping time (in man-hours per unit of surface area) of groups of heats in chronological order.

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Spectrographic Analysis

By Charles C. Nitchie*

Introduction—The fundamental basis of spectrographic analysis is the fact that every element, when converted by heat or electric discharges into the form of a luminous gas or vapor, emits light which is definitely characteristic of that element. A simple illustration of this phenomenon is the flame test, frequently used by the chemist for the qualitative indication of the alkali and alkaline earth metals. He introduces a fragment of material into the colorless flame of a Bunsen burner. If the flame is colored a bright yellow, he concludes that the element sodium is present. A violet color indicates potassium; a deep red, lithium; or a yellow-green, barium.

A test of this kind, however, can be used to only a limited extent. Relatively few of the elements emit their characteristic radiations at the temperature of the Bunsen flame. Few of them yield light so nearly monochromatic that a visual observation of the color of the flame can provide a safe basis for identification. Moreover the eye sees only an integrated average when more than one color is present and cannot separate a complex color into its components. Consequently, visual observation would be totally inadequate for the analysis of mixtures of two or more elements. For these reasons color is usually disregarded in work of this kind, radiations are designated by wave lengths and recourse is had to instrumental methods of observation which permit the clean cut separation and accurate measurement of the wave lengths emitted by the elements under consideration. The instruments used are the spectroscope and spectrograph, the former for visual observation, the latter photographic.

The Spectroscope—The spectroscope is of more limited value than the spectrograph for metallurgical analysis. Its use is confined to the comparatively narrow band of radiations which the eye can see whereas many of the elements emit their strongest and most characteristic radiations in the ultra-violet or infra-red which are invisible. Furthermore, with the spectroscope, specific search must be made for the lines of each individual element, in order that its presence or absence may be established. This search must be made while the sample is in the luminous vapor condition, with the probability that some will be missed because they have been completely expelled from the sample during the time when others were being observed.

The Spectrograph—The spectrograph is free from the limitations of the spectroscope. The photographic plate records not only the visible but also the ultra-violet and when suitably sensitized, a considerable portion of the infra-red. It records all radiations simultaneously and provides a permanent record from which the essential facts may be read at any time, even though the sample is no longer available. Its response to radiation is cumulative so that, with sufficiently long exposures, readable impressions can be obtained from radiations too weak to be observed visually. For these reasons the spectrograph is much to be preferred for analytical work and is the instrument that will be discussed here.

Spectrographs are of two major types, one using a prism, the other a diffraction grating to disperse the spectrum. The diffraction grating has the advantage that it produces a spectrum that is nearly "normal," that is, one with the same dispersion at all wave lengths, so that two lines, differing from each other in wave length by a given amount, are separated by the same distance on the photographic plate, regardless of wave length. With the prism, dispersion is much greater at short wave lengths than at long, with the result that the spectrum is more crowded in the long wave region and wave lengths cannot be measured as accurately there as in the short wave length range. This advantage is largely offset by a number of limitations, the most serious one being the fact that good gratings are difficult to obtain, their manufacture being attended by so many difficulties and uncertainties that no commercial manufacturer has found it possible to undertake their production. Less serious objections are the presence of "ghost lines" in the spectrum, due to slight irregularities in the rulings and the overlapping of successive orders of spectra, which sometimes introduce uncertainties in interpreta-

*Bausch & Lomb Optical Co., Rochester, N. Y.

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tion. For these reasons, grating spectrographs are not extensively used for spectrochemical analysis and are not considered in the following discussion.

In its simplest form (Fig. 1) the prism spectrograph may be thought of as a photographic camera, adjusted and focused to take pictures of a narrow slit through which comes the light to be examined. Between the lenses which form the image of the slit on the photographic plate is placed a prism which by refraction, bends the light, the amount of bending being determined by the material

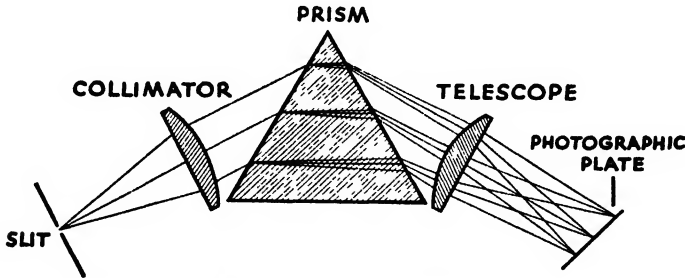


Fig. 1—Simple spectrograph.

of which the prism is made, the angle between its faces and by the wave length of the light. Light of short wave length is bent more than that of long wave length. If, now, the slit is illuminated with red light of a single definite wave length, the light will be bent to only a slight degree on passing through the prism, and the picture of the slit will be formed by the lenses toward the right-hand end of the photographic plate. If the slit is illuminated with light of shorter wave length, say violet, the bending will be more and the slit image will be formed

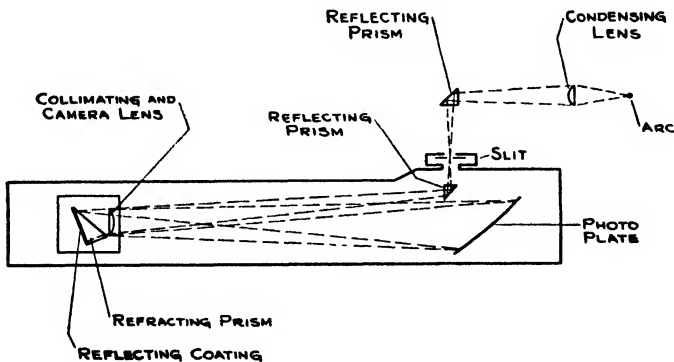


Fig. 2—Optical system of Littrow type spectrograph.

farther to the left. Ultra-violet radiation is of still shorter wave length and consequently undergoes still more deviation, the slit images of the shortest wave lengths being formed at the left end of the plate.

If the light entering the slit is made up of more than one wave length, each will form a separate picture of the slit and these pictures or "spectrum lines" will be distributed along the plate in positions corresponding to the wave lengths of the radiations producing them. There will thus be no difficulty in detecting with certainty any one wave length in the presence of others, provided the entrance

slit is made sufficiently narrow to avoid overlapping of images, when the radiations to be distinguished differ but slightly in wave length. The wave length corresponding to any line can be determined by measuring its position in the spectrum with reference to lines of known wave length. Since the radiation emitted by each element is made up of certain definite discrete wave lengths which are always the same regardless of what other elements are present in the substance under investigation, and since these wave lengths are accurately known and are available in published tables, it is possible to identify each line in the spectrum from its wave length and thus to gain a complete knowledge of the composition of the substance.

Some elements like the alkali metals yield spectra that are relatively simple, containing but a few lines. Others like iron, nickel, and tungsten yield highly complex spectra, with thousands of individual lines. This must be kept in mind when selecting a spectrograph, for a particular purpose.

These instruments are made in a number of sizes and types, with corresponding differences in dispersion and resolving power.

The dispersion of a prism is the separation it will give between different wave lengths. Strictly it is the difference in the angles at which two rays, differing in wave length by one unit,* emerge from the prism.

It is usually more convenient with a spectrograph to consider what is termed the linear dispersion, the number of Å corresponding to a separation of 1 mm. on the photographic plate. This takes into consideration not only the angular dispersion, but also the focal length of the lens which focuses the lines on the plate, since the greater the distance at which the lines are focused, the greater will be the separation of two lines with a given angular separation.

Resolving power is a measure of the ability of the prism to separate two lines differing but slightly in wave length. It bears the same relation to dispersion in a spectrograph as that between resolving power and magnification in a microscope. Just as no amount of magnification can reveal details of structure with a microscope, when using an objective of too low resolving power (determined by its numerical aperture) so, in a spectrograph, no increase in the linear dispersion will serve to separate close pairs of lines unless the prism used has the necessary resolving power, which is determined, for prisms of a given refractive index and angle, by the size of the prism. All prisms having the same refractive index and angle between refracting surfaces have the same dispersion regardless of size, but their resolving powers will vary in direct proportion with their sizes provided the beam of light which passes through the prism is broad enough to fill the entire length of the refracting surfaces with light. This, of course, means that the collimating and camera lenses must also be of proportional sizes.

It is thus obvious that to obtain satisfactory results in the analysis of materials that yield complex spectra, in which the lines are numerous with but small differences in wave length, it is necessary to use a spectrograph with a large prism and lenses to give the required resolving power and with lenses of long focal length to make that resolving power effective.

*Wave lengths are usually expressed in Angstrom units (symbol, Å). The symbol I.Å. (International Angstrom) is sometimes used to indicate that the unit used is based on the present International Standard, which by agreement assigns to the red line of cadmium the wave length 6438.4696 I.Å., a value determined by means of the interferometer in comparison with the international standard meter.

$$1 \text{ Å} = 0.1 \text{ m}\mu = 10^{-7} \text{ mm.}$$

The visual spectrum includes wave lengths from about 4000-7500 Å. Those shorter than 4000 Å comprise the ultra-violet and those longer than 7500 Å the infra-red regions.

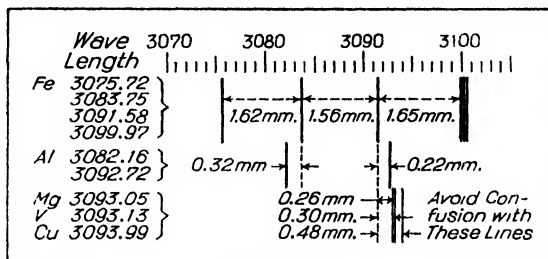


Fig. 3—Index for the identification of aluminum lines.

Size of Spectrograph—There are, of course, many materials the spectra of which do not require the use of large spectrographs. Most of the common nonferrous metals have comparatively open spectra with little danger of confusion. For such, a spectrograph of moderate dispersion and resolving power will usually be sufficient, although even then difficulties may arise if constituents are present which give lines close to those of others. It is a wise precaution, therefore, when investing in instruments of this kind, to make sure that the one selected is adequate to give unquestionable results on all analytical problems that are likely to arise.

Spectrographs of small and moderate sizes are usually arranged in the manner indicated in Fig. 1, the light entering the slit at one end and passing through the collimating lens, prism, and camera lens to the photographic plate at the other end. With large instruments, however, this arrangement is not so convenient as that known as the autocollimating, or Littrow type (Fig. 2).

The slit is placed at the same end as the photographic plate. But one lens is necessary and the prism has a metallic reflecting coating applied to its back surface. Light entering the slit is directed to the lens which renders the rays parallel and passes them on to the prism where they are refracted and strike the reflecting surface normally. They are reflected back along their incident path, are further refracted on emerging from the prism, and again pass through the lens which focuses the spectrum on the photographic plate. Several advantages result from this arrangement. The total length of the instrument is but half that of one of the conventional type and of the same focal length. The "around-the-corner" structure is avoided, permitting a straight line construction which occupies less space in the laboratory, is easier to handle when the instrument has to be moved or shipped, and makes possible a more convenient arrangement for operation. The light source and photographic plate holder can be brought near together, so that all manipulation is brought within reach of the operator at one position. Furthermore, it requires but a single lens and a prism of but half the thickness of that required by the other type, a consideration which is particularly important in the case of quartz optical parts because of the scarcity and high cost of quartz of large size and good optical quality.

If the instrument is to be used only for the recording of the longer wave lengths of the spectrum, glass optical parts may be used throughout the system. If, however, the ultra-violet is also to be observed, glass will not serve as it is opaque to wave lengths shorter than about 3600 Å. Since most of the metals have their strongest lines in the region of shorter wave lengths, a spectrograph to be used for general metallurgical analysis must be provided with optical parts that will transmit these wave lengths. Quartz is usually employed, as it has the requisite short wave transmission and is found in natural crystals large enough for the manufacture of prisms and lenses of the necessary size.

The Light Source—Various devices are used for exciting the radiations. They include: (1) The Bunsen burner; (2) the oxy-acetylene flame; (3) the electric arc; (4) the high tension spark; (5) the vacuum discharge tube; (6) the electric furnace; and (7) the explosion of fine wires by heavy condenser discharges.

The Bunsen Flame—The Bunsen flame, with its relatively low temperature, will excite the radiations of the alkali and alkaline earth metals and a few others, but is not effective with most of the elements that are encountered in metallurgical work. Consequently it is rarely used.

The oxy-acetylene flame is much hotter than the Bunsen flame and will excite radiation from many more elements. It has been used by Lundegardh¹ and others with considerable success on a variety of materials. The sample is used in the form of a solution which is introduced into the gas stream as a fine spray, with the aid of a special form of atomizer.

The electric arc is the light source most generally used. The sample may take any form that may be convenient. Rods or reasonably heavy strips of metallic samples may be used as electrodes and the arc struck between them, with sufficient resistance in series to give the required current, usually 5-15 amperes. This is the most satisfactory form when the metals are of sufficiently high melting point to withstand the high temperature of the arc without melting down. Since the metals usually have high heat conductivity it is often possible to use metals of relatively low melting point in this way if the electrodes are of large cross section

so that the heat is carried off rapidly from the points where the arc is struck, and only the tips reach the fusion temperature. The main advantage of the use of "self-electrodes" is the fact that the light emitted comes entirely from the sample and there is no chance for confusion with extraneous lines in the spectrum which are always present when supporting electrodes of other materials are used.

Sometimes it is impossible to obtain the samples in forms that can be used directly as electrodes. Small fragments, drill chips, hack saw dust, powders, and solutions are usually introduced into a cavity drilled in the tip of a pure carbon rod which is mounted as the lower electrode of the arc, a second rod of the same pure carbon serving as the upper electrode. Artificial graphite is the form of carbon most commonly used. Special grades are available commercially from which metallic impurities have been removed either by repeated heating at the temperature of the graphitizing furnace, or by chemical treatment followed by such heating. The grade which is most widely used may contain minute amounts of boron, calcium, copper, magnesium, silicon, titanium, and vanadium, the lines of which will appear in the spectrum. They may be allowed for, to a large extent, by photographing the spectrum of the blank electrodes alongside that of the sample and ignoring lines common to both, if no stronger in the sample spectrum than in the blank. This procedure is subject to some uncertainty as the impurities may not be evenly distributed throughout the graphite. Furthermore the intensities of electrode impurity lines are considerably affected by the other elements present in the samples, some elements having the effect of enhancing, others of suppressing the lines of other elements. For these reasons it is not possible to make exact allowance for electrode impurities from the blank electrode spectrum. In critical cases, when the analyst must be certain of the presence or absence of minute traces of the elements that do occur as impurities in the ordinary grade of spectroscopic graphite, it is necessary to use more highly purified graphite from which these impurities have been more completely eliminated. A method for purifying electrodes is described by Standen and Kovach.²

One source of occasional difficulty with the carbon arc is the presence in its spectrum of numerous broad and intense bands due, not only to carbon but also to molecules of its oxides and nitrides (cyanogen) formed when the arc burns in air. They are often so strong as to hide completely the lines of other elements present in the sample and having wave lengths lying within the bands. It is a fortunate circumstance that comparatively few of the metals have their most important lines in the regions so affected, and most of these also have lines of good intensity at wave lengths where they will not be subject to this type of interference. For the few cases in which it is necessary to observe weak lines in the regions covered by the carbon bands it is sometimes necessary to use supporting electrodes of other materials than carbon. Copper or silver electrodes are sometimes employed. They are not so effective as carbon in bringing out extremely small traces because they do not reach so high a temperature and consequently do not vaporize the samples as readily as does the carbon arc.

Direct current is necessary for the maintenance of an arc between metallic electrodes or those of graphite. Alternating current will not serve. The arc can be operated from a 110 volt d.c. line with care and close attention, but greater steadiness and freedom from interruptions are insured by using a higher line voltage, 220-250 volts. A rheostat is connected in series with the arc to regulate the current. This will vary with the nature of the samples and the purpose of the analysis. No definite rules can be set down as the most favorable conditions must be determined by experiment for each problem as it arises. Highly volatile samples usually require lower amperage than those of a more refractory nature in order to avoid too rapid volatilization. Some materials, such as some of the alloy steels, throw off a shower of sparks, consisting of particles of white hot metal, which may embed themselves in the surface of the condensing lens if too high current is used. On the other hand, too low a current will often fail to produce the necessary electrode temperature to volatilize a highly refractory sample and will thus unduly prolong the exposure.

The amount of sample to be used will depend on many conditions, including the nature of the material, the form in which it is received, the elements to be detected or determined and the concentrations in which they are present. A fraction of a milligram will often suffice for an indication of the major constituents.

Fifty milligrams will usually permit a complete analysis for both major constituents and impurities present in minute traces.

Arc excitation yields a spectrum which permits the detection of all the metallic elements, but only a few of the nonmetals. Hydrogen, oxygen, nitrogen, the halogens, and the rare gases do not emit their spectra in the arc. Phosphorus and selenium do so at relatively high concentrations, but are not nearly so sensitive as most of the metals in the range of wave lengths readily available with ordinary spectrographs and photographic emulsions. Their strongest spectrum lines fall so far out in the ultra-violet as to require, for the detection of small amounts, the use of a vacuum spectrograph and specially sensitized plates. The same is true of sulphur which, however, also yields lines of considerable intensity in the near infra-red. With the recent development of infra-red sensitive plates there is reason to believe that sulphur can be detected in amounts comparable with many of the metals. Carbon yields a few strong lines and, when the arc is burned in air, numerous complex bands due to oxide and nitride molecules. Attempts have been made to develop methods that would permit the spectrographic detection and estimation of carbon in iron and steel but without much success, and there is at present little prospect that the spectrograph will provide a substitute for chemical methods for carbon analysis.

The high tension spark is extensively used in much the same way as the arc, samples and electrodes being of a similar character. The electric discharge, however, is quite different. In the first place, it is at much higher potential, commonly from 5000-20,000 volts. Secondly, it is usually an alternating current discharge drawn from an induction coil or, more commonly from a step up transformer operated from the ordinary 110 volt, 60 cycle supply. The amperage is much less than with the arc and the electrodes do not reach the high temperature of arc electrodes. Consequently the amount of vapor raised to incandescence is far less than in the arc. The spark is usually less sensitive in the detection of extremely small amounts of minor constituents and impurities, and longer exposures are required to obtain comparable line densities on the photographic plates.

The intensity of the spark is greatly enhanced by inserting a condenser in the high tension circuit, usually in parallel with the spark. This may be a Leyden jar or a plate condenser with glass, mica, or oil dielectric.

The spectrum of the spark will include not only lines of the sample and electrodes but also numerous air lines emitted by the atmospheric gases. The air lines can be largely eliminated by inserting a self-induction coil of a few microhenries in series with the spark.

Because of the high potential in the spark, the spectra produced by it often differ in important respects from those produced by the arc. Certain lines will be brought out strongly in the spark spectrum that are weak in or completely absent from the arc spectrum. Some lines that are prominent in the arc spectrum will be suppressed in the spark. These differences are due to the fact that most of the radiations in the arc arise from neutral atoms, those which still retain their full complement of electrons, whereas in the spark many of the atoms have lost one or more electrons—in other words are ionized—and consequently behave like distinctly different elements. For this reason care must be exercised to avoid confusion when comparing arc with spark spectra of any material. Some "spark lines" will usually appear in the spectrum emitted by the arc and some "arc lines" in that emitted by the spark, but their relative intensities will differ with the prevailing electrical conditions and also with the particular combination of elements in a given sample.

The spark has some advantages over the arc that recommend it for certain purposes. It will usually maintain its position with greater constancy, having less tendency to wander from place to place on the electrodes thus requiring less attention on the part of the analyst to keep it properly lined up with the spectrograph. For this reason, too, it can be used more readily for the examination of restricted areas in a sample. Small spots, where segregation is suspected can be examined by directing a spark to the suspected spot, with less danger of interference from the surrounding material than would be experienced with the arc. Because of the lower electrode temperature it is possible with the spark to obtain the spectrum of a specimen without altering its form or removing any appreciable amount of material. This is sometimes desirable in the analysis of rare specimens, items of

evidence in criminal cases or other objects, the original form of which must not be changed.

The principal disadvantages of the spark are its lower degree of sensitiveness in detecting extremely small traces and the highly objectionable noise produced by the condensed spark.

The *vacuum discharge tube* is used in obtaining the spectra of gases. The familiar neon sign is an example of such a tube in which an electric discharge at fairly high potential is passed through the gas at relatively low pressure, the light being observed either through the wall of the tube or through a suitable window applied over the end. Such devices are of little application in work with metals, although there is a possibility that methods could be developed for nitrogen in which these tubes could be used.

The *electric furnace*, as a means for exciting the spectrum, is used in the study of the emission from metallic vapors at different temperatures. It has provided important data for those who are concerned with the origin of spectra and the energy relations involved in the emission of different spectral lines, but has not been used for spectrochemical analysis.

The *wire explosion method* involves the explosion of a fine wire of the metal to be analyzed by passing through it an instantaneous current of high amperage from a condenser of large capacity charged to a high potential. In this way enormously high temperatures are obtained and light of great intensity is emitted. The method has been successfully applied to the analysis of the fine tungsten wires used as filaments in incandescent lamps and vacuum tubes. It has also been used for the analysis of other materials by coating the wire before explosion with a film of the sample material. This method has not come into general use but appears to have promising possibilities for some types of work.

Illumination System—The way in which the light from the source is introduced into the slit of the spectrograph has a great deal to do with the quality of the lines as photographed on the plate. A detailed discussion of the many factors involved is beyond the scope of the present article. An excellent demonstration, with experimental data has been presented by Stockbarger and Burns.³ No one method will provide the best illumination for all purposes.

The sharpest lines will be obtained when a small source is placed at a considerable distance from the slit, with no condensing lens between. This, however, utilizes but a small part of the emitted light and necessitates undesirably long exposures.

Another method is to place a diffusing screen, such as a ground quartz plate between the light source and the slit, illuminating by diffused light. This insures more even illumination of the whole length of the slit than the method using a condensing lens, but has the disadvantage, when used with the carbon arc, that it introduces into the spectrograph not only the light from the arc proper, but also a flood of white light from the hot electrode tips, producing a strong background of continuous spectrum.

By far the most common method of illumination is to focus a magnified image of the source on the slit by means of a condensing lens. While this does not produce so sharp lines as those obtained with the first method, they are sufficiently sharp for most practical purposes and the method has several distinct advantages. More light is introduced into the spectrograph, resulting in shorter exposures. White light can be excluded by using sufficient magnification to throw the images of the electrode tips above and below the open length of the slit, thus limiting the light entering the spectrograph to that from the arc or spark. Furthermore, once the condensing lens has been properly located, it provides an accurate indicator for locating the light source in the optical axis of the spectrograph. All that is necessary is to bring the source into such a position that its image falls on the slit.

An optical bench, rigidly attached to the spectrograph, with supports for light source and condensing lens, is the best means for securing correct alignment and maintaining it.

Sometimes it is desirable to have means for reducing light intensity, in order to avoid overexposure of the photographic plate, when the exposure time must be extended to permit complete volatilization of a refractory sample. Such a

means is provided by an adjustable sector disc, rotating in the path of light between condenser and slit and cutting off any desired fraction of the full illumination. The speed of rotation is immaterial so long as it is not so high as to set up excessive vibration. All that counts is the ratio of open to closed sectors.

Photography of the Spectrum—The photography of the spectrum differs in no essential respect from pictorial or metallographic photography. It is really somewhat simpler than either since the spectrograph is either permanently focused, requiring, with small or medium instruments, no adjustments to insure a sharp picture or, with the large size instruments but the setting of a couple of scales to predetermined figures to bring any desired portion of the spectrum into focus on the photographic plate.

Plates are more generally used than films since they provide a more accurate surface on which to focus the spectrum. The slight curvature that is required to insure sharp focus over the full length of the spectrum can usually be applied to a plate without danger of breakage, and without any of the resultant lateral curvature that is apt to distort the spectrum when films are used.

Almost any of the commercial photographic emulsions can be used. Ordinary plates are satisfactory for the ultra-violet and the short wave portion of the visual range. Panchromatic plates must, of course, be used when it is necessary to record longer wave lengths, up to the red end of the visual spectrum. Specially sensitized plates are now available which extend the range that may be photographed well beyond the visual region into the infra-red. Others make possible the photography of the short wave, ultra-violet in the region to which the gelatine of the emulsion is not transparent.

Slow plates are generally more satisfactory than fast ones as they have finer grain, and show better contrast and resolving power. Their slowness is not a disadvantage as it is usually necessary to give rather long exposures to permit time for the complete vaporization of the sample and thus to insure a correct indication of the proportions of the constituent elements, those that are highly volatile and come off rapidly from an arc as well as those that are refractory and evaporate more slowly. Exposures of 2 or 3 min. are usually required with small samples of metals in graphite electrodes. Slags and refractories may require 5-10 min. to insure complete volatilization. When metallic electrodes made from the sample material are used with the arc the case is somewhat different. It is impossible to insure the volatilization of a definite amount of material; long exposures may be accompanied by a gradual change in the proportions of constituent elements at the points where the arc has struck and short exposures will frequently yield more consistent results than long ones.

Qualitative Analysis—If the fully developed spectrum of a pure element is examined it will be found to include a number of lines of different wave lengths. With some elements the number is small, with others large. Some lines will be of high intensity, some weak, some exceedingly faint. If the spectrum is that of a material in which the given element forms only a part of the whole, other conditions being the same, the lines of that element will, in general, appear with decreased intensity. Those that were weakest in the full spectrum will fail to appear at all. At still lower concentrations other weak lines disappear until, at the lowest concentrations at which the element can be detected at all, only one or two lines remain. These are the so-called *raies ultimes*, the lines that are the last to disappear when the dilution is carried to the limit. De Gramont⁴ has made a thorough study of this phenomenon and has published a table giving for each of a large number of the elements, the wave lengths of these most persistent lines, together with a few which, while not so persistent as the *raies ultimes*, can still be observed at low concentrations.

In qualitative analysis, the identification of the elements present in a sample requires only a systematic search for these highly persistent lines of each element. It is not necessary to go through the tedious process of identifying every line in the spectrum. If the *raies ultimes* of an element are found, they provide proof of its presence in the sample. If they are absent, it is useless to look for other lines of the element in question, as they will certainly be missing.

The most convenient and at the same time the most certain procedure in qualitative work is to locate the lines in question by their positions in the spectrum

with reference to neighboring lines of known source and wave length, either in the same spectrum or in a standard spectrum photographed on the same plate adjacent to the one under examination. The iron arc spectrum is almost universally used as a standard, except in the case of spectra taken with instruments of low resolving power and dispersion. The iron spectrum contains many lines, well distributed throughout the range of wave lengths used in analysis. Therefore, convenient reference lines can be found near to those to be identified wherever they may be. Their wave lengths have been accurately determined and are available in published tables. They occur in groups that can readily be recognized after a little practice so that the experienced spectroscopist has little difficulty in locating and identifying the lines to be used as bases of reference.

Wave lengths of sufficient accuracy for most purposes can be determined by measuring accurately the distance on the plate between two reference lines, one on each side of the line to be identified, and also the distance between the latter and one of the reference lines. Knowing the wave lengths of the reference lines, simple arithmetical proportion gives that of the unknown. The computation assumes a linear relationship between wave length and line position. This of course is not strictly true in a spectrum taken with a prism spectrograph, since the dispersion increases with decrease of wave length. If the reference lines are not far apart, however, the error is small and the calculated wave length is usually close enough for correct interpretation. Occasionally it may be necessary to measure with greater precision than is attainable by linear interpolation. Such a case would arise when two or more elements had spectrum lines of so nearly the same wave length that the identification was in doubt and no other lines of these elements were available as a check. It would then be necessary to select three or more reference lines in the standard spectrum, measure their positions and that of the unknown line with the greatest possible precision, using an accurate measuring microscope, and compute the wave length with the aid of the Hartmann interpolation formula. Space does not permit a detailed discussion of this formula here, but it may be found in the larger treatises on spectroscopy.⁸ It involves rather laborious calculations to evaluate the constants in the equation for a given instrument and spectral region, but when properly applied gives results of the highest precision. A considerably simpler formula, giving very nearly the same results, has been suggested by Russell and Shenstone.⁹ A still simpler procedure that is more accurate than linear interpolation is the graphical method of plotting line position against wave length on co-ordinate paper, using a sufficiently large scale to permit readings to the required precision and enough known lines to define accurately the form of the curve.

A great deal of time may be saved by the spectroscopist who is doing much qualitative analysis, if he will prepare a diagram, similar to Fig. 3, for each element, when first he has occasion to identify it, noting the distances, as measured on his plates, between reference lines and those of the element involved. He will thus gradually build up an index that will enable him to identify the important lines by simple measurement, without having to repeat the calculations. An excellent precaution also is to list beside each diagram the wave lengths of lines of other elements that might be confused with the one under consideration with their distances from the same reference lines. This will serve as a warning if special care in measurement is required to insure correct identification.

Quantitative Analysis—As mentioned in the previous section, the intensities with which the lines of an element are brought out in the spectrum under constant conditions of excitation and photography bear a direct relation to the amount of that element present in the sample. When much is present, the most prominent lines are strong; when little is present all lines are weak. This provides the basis for quantitative analysis.

The excitation and photography of the spectrum are essentially the same in quantitative as in qualitative analysis. More care is required, however, to maintain constant conditions at all stages of the procedure, since there are many variables that may influence the densities with which lines are brought out on the photographic plate and these must be kept under control if results of reasonable accuracy are to be obtained.

Comparison of Spectrum Lines—All quantitative methods depend on the comparison of the densities of the spectrum lines of the constituents to be determined, with those of the same lines in the spectra of standard samples of similar general

composition but with different known amounts of these constituents. This comparison is sometimes direct, sometimes indirect.

The simplest, but at the same time, the least accurate way is to compare the spectrum of the sample directly with a series of spectra, previously prepared from the standards, noting among the latter the concentration at which the lines of the element in question are equal in density to those in the sample spectrum. The concentration in the sample is then assumed to be the same as that of the matching standard. If no exact equality is found the concentration is estimated between the two standards, one of which shows the lines a little stronger, the other a little weaker than those of the sample. With experience such differences can be estimated fairly closely and results accurate to 20 or 25% of the amount involved can be obtained. Sometimes this degree of precision is all that is needed as, for instance, when classifying mixed stocks of materials, or determining the general type of an alloy. Usually, however, a higher degree of precision is desirable.

Among the factors that are most difficult to keep constant in the procedure just described are those involved in the photography. Plates, even of the same brand, vary somewhat in their behavior. Composition and temperature of the developing solution may change, with the result that spectra on different plates may not be strictly comparable. These variations can be eliminated to a large extent by photographing standards and samples on the same plate. This, of course, increases the time required for making the analysis but materially improves the precision of the results, since all spectra will then have had the same treatment. It is the procedure specified in the methods adopted as tentative standards for the analysis of certain metals by the A.S.T.M. in 1935. While not so precise as the methods next to be described it yields results that may be relied upon to about 10% of the amounts involved and has the advantage that no accessory equipment is needed for density measurements.

Internal Standard Method—While the precaution of photographing sample and standard spectra on the same plate eliminates errors due to variations in photography, there still remains the possibility that variations in the light source may affect the accuracy with which the spectra can be compared. Line densities may be appreciably increased or diminished by changes in electrical conditions in the excitation circuit between exposures, or by variation, as in the solution method, in absorbing power of the graphite electrodes. Errors due to the former cause are largely eliminated by the "Internal Standard Method" of Gerlach and Schweitzer.⁷

This is an indirect method in which the lines of the elements to be determined are not compared directly with the same lines in separate spectra of standards, but with selected lines of another constituent in the same sample. It is necessary that this second constituent be present in constant amount in all samples of a given material, or that it vary in amount only as a result of the variation in the amount of the constituent to be determined. Evaluation is based not on the actual densities of the lines in question but on their ratio, which is correlated with concentration by preliminary calibration with standards. For example, given the problem of determining the manganese in a steel, the iron content will be essentially constant in all samples of a given type, and therefore the iron lines in the spectrum can be used for comparison with the manganese lines. A preliminary calibration is first made by photographing the spectra of three or more samples which have been accurately analyzed and are known to contain different amounts of manganese from the lowest to the highest that may be expected in that grade of steel.

One of the manganese lines is selected which shows a suitable intensity variation over this range of concentration. It must not be a very strong line because beyond a certain density there may be too small a change in density with concentration to give good results. Likewise it must not be too weak, for a similar reason. The line should be one having a density that falls within the straight line portion of the characteristic curve of the photographic plate, the curve connecting light intensity and the density of the image produced by it on the plate. A fairly close approximation to this requirement is obtained if the line selected is clearly defined throughout the range and is distinctly gray, not black at the highest concentration.

From the many iron lines in the neighborhood of this manganese line one is selected to serve as the basis of comparison. It should have a density within

the range of the series of manganese lines. However, instead of showing variation in density throughout the series, this iron line will be of practically the same density in all, since the amount of iron is practically the same in all the samples. This line should be fairly near the manganese line in the spectrum since the rate of variation of density with light intensity is different at different wave lengths. In a typical series the manganese line in the spectrum of the sample of lowest manganese content will be considerably weaker than the iron line; at some higher concentration the two will be of approximately equal density, while at the highest concentration the manganese line will be stronger than the iron line. It is these ratios that are to be correlated with concentration, not the actual densities. In this way compensation is secured for variations in the light source. If all conditions could be kept absolutely the same during the series of exposures, there would be no need for the reference lines and the densities of the manganese lines could be used as a measure of concentration. Fluctuations are unavoidable, however, but since they affect both the manganese and iron lines to the same extent the ratio will remain practically constant, even though the actual densities differ.

The line densities are then measured with some form of density comparator or microphotometer. Several forms are used. One typical form uses the spectrum plate as a "lantern slide" and projects a magnified image of the portion of the spectrum containing the lines to be measured on a screen in the center of which is a narrow slit through which light can pass to a photocell. The image of the line to be measured is brought into position over this slit, so that the light reaching the sensitive surface of the cell is only that which has passed through the line on the plate. A galvanometer connected with the cell is deflected by an amount proportional to the cell illumination, that is, to the transparency of the line, and the deflections are read on a scale conveniently mounted in the front of the instrument. If any appreciable background of continuous spectrum is present on the plate it is necessary to allow for it by taking a reading in this background near to the line and expressing the line density as the difference between the two readings.

In each spectrum the two lines, manganese and iron, are measured and the ratio of the corrected readings is plotted against the corresponding concentration on coordinate paper. A curve is then drawn connecting the observed points. This curve, then, provides the means for determining the manganese content of any sample of the same type of steel.

Logarithmic or Wedge Sector Method—Another method of measuring line intensities is that using the logarithmic wedge sector or logarithmic spiral to vary the exposure over the length of the slit. This is an opaque disc, the periphery of which is cut in the form of a spiral, the difference between the shortest and longest radii being equal to the length of the slit. When this is properly mounted in front of the slit and rotated, one end of the slit receives light continuously during the entire time of exposure. Successive elements in the length of the slit receive shorter and shorter exposures, until at the other end they are but instantaneous flashes at each revolution of the disc. The result is that strong radiations are recorded on the plate as long wedge shaped lines while weak ones produce short lines, the length being determined by the proportion of the total slit length that receives sufficient illumination to produce a developable impression on the photographic plate. Line intensities are then read by measuring the lengths of the lines. This method has come into considerable favor since it requires no special instruments to measure intensities, and the readings can be made as soon as the plate has been developed without waiting for fixing, washing, or drying, thus saving an appreciable amount of time when speed is important. Its principal limitation is the uncertainty in determining the point at which the line ends, where it is gradually fading out to zero density. Uncertainties in measurement are sometimes reduced by using, instead of a continuous spiral disc, one cut as a series of steps so that the line appears on the plate as a series of clearly defined segments, the densities of which vary from one end to the other. Another device is to cross the slit with a "gridiron" of fine wires or opaque rulings regularly spaced on a transparent plate, the result being to break up the line into distinct segments. In either case the length of the line is measured by counting the number of segments or breaks that can be seen. The "internal standard" method of comparison is used with these devices as well as in the procedures depending on photometric measurements.

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Metallographic Polishing

By J. R. Vilella*

Sampling—The metallographic specimen, like any other sample, to be of value must be truly representative of the parent metal, both as to chemical composition and physical condition. If it is not, the finest polishing, etching and photomicrography are wasted effort. Generally the purpose of the investigation and the shape and condition of the material suggest the position from which the specimen or specimens should be cut, but there are some general rules which, if observed, help to obtain adequate specimens:

1. If the object of the investigation is to determine the cause of a failure, the specimen should be obtained from a position close to where the failure was initiated. It is also advisable to obtain one or more specimens from a position some distance from the failure in order to compare the structures of sound and failed metals. Comparisons of this type usually yield valuable clues.

2. When working with rolled or forged materials transverse and longitudinal sections should be examined. This is equally important whether the purpose of the examination is to study the nonmetallic inclusions or the structure. If the material has been cold reduced, specimens in the direction of working are indicated.

3. In wrought or wrought and heat treated materials it is advisable to include in the specimen a portion of the outer skin, so that decarburization and other surface conditions may be noted.

4. If the metal is suspected of segregations, several specimens from different positions should be examined.

Cutting the Specimen—When the location of the specimen has been settled, the specimen may be cut by means of a hack saw, a band saw, a cutting-off wheel, or in the case of hard and brittle materials, it may be notched and fractured. Occasionally it is necessary to resort to flame cutting in order to obtain suitable specimens from large sections.

Regardless of the means employed it is essential to avoid heating and dragging the metal at the cut surface. With hardened steel, heating is particularly undesirable because it is likely to temper. To minimize heating during cutting, a hack saw should be used, with proper lubrication, for all specimens that can be cut by this means. Hard materials should be cut with cutting-off wheels operating under water. Dragging of the surface metal is a common defect encountered in specimens of soft materials. It can be minimized by lubrication of the saw blade. The structure of a flame cut surface is, obviously, not representative of the metal, and therefore not a suitable metallographic specimen.

Specimen Size—Whenever possible, for convenience in subsequent handling, the size of the specimen should be within the limits of $\frac{3}{8}$ to 1 in. sq. (or dia.) and somewhat less in thickness. Smaller specimens are not only difficult to handle but almost impossible to polish without rounding the edges excessively. Larger specimens are difficult to finish without scratches and without dislodging the nonmetallic inclusions. Specimens in which the height exceeds the linear dimensions of the face to be polished are difficult to grind with the necessary flatness. It is not always possible, however, to get specimens of comfortable size. Sheet metal, wire and a multitude of other small articles are definitely of too small cross section to handle comfortably. These must be mounted either in clamps, molding plastics, or in fusible alloys.

Mounting of Specimens—The method to use depends on the purpose of the specimen, its shape, the maximum temperature it can stand without alteration of its structure and, of course, on the equipment available at the laboratory.

Steel clamps of adequate shape and dimensions are best adapted to rectangular and square specimens having straight edges. They constitute the most satisfactory means of preserving the flatness of the edges; in fact, they are almost indispensable, even when working with large specimens, when the edges are to be examined at intermediate or high magnification. In general, the degree of roundness of the edges is proportional to the difference in hardness (or abrasion resistance) between the specimen and the mounting material. For this reason, when maximum flatness of the edges of hard specimens is needed, even clamps, if made of soft metal, are not entirely adequate. In such cases the clamp should be made of a material which

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approximates the hardness of the specimen. However, to obtain consistently satisfactory results certain other precautions must be observed. In the first place, clamps often interfere with the etching of specimens of dissimilar composition, as for example, stainless steel mounted in carbon steel clamps; secondly, their rigidity makes it difficult to obtain close contact between clamp and specimen, with the result that a trace of the etching reagent often creeps up and stains the edge it was desired to examine. A satisfactory way of overcoming these difficulties is to insert a strip of soft copper between the clamp and specimen. In this manner, a tight contact is produced without in any way damaging the edge, and at the same time the interference with etching is overcome, for copper is hardly attacked by the usual etching solutions for steel.

The use of fusible alloys as a mounting material, such as Woods metal, has, because of its tendency to smear and because of its inability to prevent rounding of the edges, been largely superseded by harder plastics such as Bakelite, Lucite and Tenite, which have proved invaluable to those handling a large number of small specimens.⁴ Their chief merits are: (1) Adaptability to specimens of any shape, (2) close contact between specimen and mounting material, so that staining due to seepage of the etching reagent is prevented, (3) relatively low molding temperature, permitting its use even for specimens subject to tempering, (4) inertness to the etching reagent, and (5) good, although not the best possible, preservation of the flatness of the edges.

Another practical and rapid method of mounting specimens in which optimum preservation of the flatness of the edges is not necessary is the following: Place a brass ring of convenient size, preferably one made oval by compressing its sides, on a smooth steel plate and pour inside the ring enough mercury to form a pool $\frac{1}{8}$ to $\frac{1}{4}$ in. deep. Push the specimen through the mercury, surface to be polished down, and hold in contact with the plate. Pour molten sulphur over the mercury and specimen, to fill the ring, and allow to solidify. This takes place rapidly. To recover the mercury, slide the assembly to the edge of the plate and collect it in a convenient receptacle. In specimens mounted in this manner the surface to be prepared is level with the walls of the ring but not in contact with it at any point and also at a considerable distance from the level of the sulphur; thus it can be polished without dragging the mounting material over the polished surface, and without contaminating the wheels with sulphur. The low melting point of the sulphur, its rapid cooling, and the fact that it never comes in contact with the immediate vicinity of the surface to be polished, minimizes the danger of altering its structure as a result of heating.

Preliminary Facing—This may be accomplished by filing, by grinding on stones or prepared papers or by machining. If filing is used, the best way to obtain a flat surface is to lay the file on the working bench and push the specimen against the cutting edges, preferably in one direction only, for back and forth rubbing tends to round the edges of the sample. More rapid and equally satisfactory results can be obtained with motor driven belt surfacers. These are not restricted to small specimens of soft materials, like files are, and when properly used, yield satisfactory flatness. Grinding stones are perhaps the least satisfactory means of obtaining a flat surface; they tend to fill up with metal, become dull in a comparatively short time, requiring frequent dressings and eventually develop grooves which round the specimen. However, with proper care, and in the hands of careful workers, these disadvantages can be largely overcome. Regardless of the means employed, care should be taken at this stage to maintain the specimen cool and to avoid deep scratches, for a deep scratch may completely alter the structure of the underlying metal. This condition has often been observed in specimens of 18-8 and other alloys susceptible to structural changes by comparatively slight cold working.

Grinding—Grinding consists of abrading the specimen with a series of grits of increasing fineness until a set of scratches is produced which is sufficiently fine to be totally eradicated in a reasonably short time with finest polishing material available. There are several satisfactory ways of carrying out this step.

1. *Grinding on Abrasive Papers*—This method consists of abrading the specimen with papers coated with aluminum oxide (emery) or silicon carbide (Carborundum) of increasing fineness. The grades most commonly used are 100, 200, 320 and 400 mesh grit; or No. 2, 1, 0, 00 and 000. This may be done either by hand or on power driven wheels. In either case, on passing from a coarser to finer paper it is advisable to rotate the specimen 90° so as to facilitate recognizing when the coarser scratches have been entirely replaced by the finer ones.

The chief merits of this method are that the nonmetallic inclusions are not dislodged, that it is comparatively easy to master and that the commercial grades of papers available are well graded as to grit size and are of uniform high quality. Its chief disadvantages are (1) that it distorts the structure of the surface metal, particularly when the papers are used after the grit has become dull, (2) that it tends to round the corners and edges of the specimens and (3) it tends to heat the specimen. However, these disadvantages can be greatly minimized by careful working.

Hand polishing is generally considered a slow and laborious process and for that reason is seldom practiced in this country. The technique of those who still use it consists of rubbing the specimen back and forth on abrasive papers stretched smoothly over a flat hard wooden block or a metal surface. Its advantages over machine grinding are less heating and less distortion of the surface metal.

In machine grinding, the speed of the wheels is of some importance. However, since the rate of cutting or abrasion depends on the linear velocity and not on the r.p.m., a higher rate of cutting is always obtained at the periphery than at the center, and likewise, the larger the disk the faster the rate of cutting at the periphery. For these reasons, recommendations as to the best speed of grinding expressed in r.p.m. are of little significance. It can be safely said that in practice high speeds are not conducive to the best results nor appreciably expedite the process. A speed of 600-700 r.p.m. for a 9 inch disk is used in the writer's laboratory. With well constructed machines free from vertical vibrations, higher speeds can be used safely.

2. Grinding on Paraffin Wheels—Disks similar to those used for grinding with papers are covered with a layer of high melting point paraffin about $\frac{1}{4}$ in. thick, machined flat and a spiral groove or a series of concentric circles $\frac{1}{8}$ in. deep inscribed on them by means of a nail or some other pointed article. The function of the groove is to hold the water and abrasive on the disk. The abrasives consist of a series of emery powders, ranging in fineness from 200 to 600 mesh, which are suspended in a soap solution and sprinkled over the revolving disks at frequent intervals. Natural emery is preferred.

An excellent modification of this method is to use instead of a paraffined disk, canvas or billiard cloth previously impregnated with paraffin. The paraffin is melted in a suitable container and the cloth immersed in it until it has absorbed all the paraffin it can hold. While the impregnated cloth is still warm and pliable it is stretched smoothly over the disk and held in place by means of a ring which fits around the circumference of the wheel. Billiard cloth is preferable for the finer abrasives and 12 ounce canvas for the coarser ones. At first the impregnated cloth will feel somewhat rough, but it will become smooth after grinding several specimens.

The merits of this method are: (1) Satisfactory preservation of the nonmetallic inclusions, (2) good flatness of the edges of the specimens, (3) less distortion of the surface metal than is produced by grinding on papers, and (4) the specimen does not heat up during grinding.

3. Grinding on Lead Laps—Two methods^{2,3} involving the use of lead laps have been described recently. Both are based on the principle that grit held firmly by the carrying medium, that is, not free to roll during grinding, does not excavate the nonmetallic inclusions, nor widens any cracks or porosity which may be present in the metal. One of these methods, originated in Sweden, is as follows: On each of three disks is deposited a layer of lead approximately $\frac{1}{4}$ in. thick and machined flat. The abrasive (emery or tungsten carbide) is applied and "fixed" to the lead lap with a fast drying varnish previously thinned with benzene. The grinding procedure is carried out in three steps after preliminary "coarse" grinding to obtain a flat surface, (1) grinding with emery of 100-40 microns in grain size, (2) grinding with emery of 50-25 microns size, and (3) grinding with tungsten carbide of grain size less than 4 microns. It is important that the surface after the preliminary grinding be as flat as possible, for if rounded the process is greatly delayed in the subsequent step, inasmuch as the lead lap cuts only in one plane. After the grit has become dull through grinding it can be "resharpened" by simply passing a brush dipped in benzene over the disk; this softens the varnish and causes the abrasive grains to turn, thus presenting a new sharp face to the specimen. The varnish rehardens in about one minute.

The advantages claimed for this method are: (1) Rapid preparation of the specimen, (2) a degree of flatness not obtainable by any of the usual metallographic polishing methods, (3) excellent preservation of the nonmetallic inclusions, (4) the

possibility of using finer abrasives and hence shortening of the time required for the final polish, and (5) lower operating cost than with abrasive papers.

The other method¹ utilizing lead laps was originated at the Bureau of Standards. It is carried out in two steps, but each step requires two disks, one for the actual grinding made of 50% lead and 50% tin alloy; and the other disk is made of high strength, fine grain cast iron, used only for charging and maintaining the flatness of the lead-tin disk.

The cast iron disk is ground in a precision surface grinder to a maximum deviation from a true plane of 0.0001 in. over the entire surface. The disk contains grooves $\frac{1}{2}$ in. apart, milled to a depth of $\frac{1}{32}$ in. with 60° milling cutter, and it is somewhat larger than the lead-tin disk. The lead-tin disk contains similar grooves but $\frac{1}{4}$ in. apart. The surface of this disk should be faced flat in a lathe before milling.

Charging of the lead-tin laps is accomplished by placing the emery of the proper grades (American Optical Co. No. 302 and 303½) mixed with water on the face of the cast iron disk and rotating the lead-tin disk, face down, upon it for about 30 sec. It is then brushed and washed until free of loose grit.

Grinding is done using water as a lubricant. Only a very gentle pressure is needed to obtain good cutting action. The advantages of this method are the same as those claimed for the Swedish method.

An automatic polishing method⁴ employing cast iron and lead laps was also recently described. It is not discussed here in detail because it requires specially built equipment.

Rough Polishing—Rough polishing is merely the last stage of grinding but because it is the most important step in the entire process of metallographic polishing, it must be treated separately. On this step depend (1) the length of time required to finish the specimen, (2) the preservation or dislodgement of the non-metallic inclusions, and (3) the thickness of the layer of distorted metal which must be removed before the true structure is revealed. This step can be carried out in several ways, of which the most frequently practiced are the following: (1) Grinding on billiard cloth or canvas with powders such as 600 alundum, emery or tripoli; (2) grinding on fine abrasive papers such as No. 0000 or 600 grit emery or Carborundum; (3) grinding with 600 or finer emery on wax disks or billiard cloth impregnated with paraffin; (4) grinding with 600 or finer emery or tungsten carbide powder on lead laps.

(1) *Loose powders on billiard cloth or canvas* produce fine even scratches, which disappear readily during the final polish and yield a surface with a minimum of disturbed metal. Their main disadvantage is that the prepared surface is likely to be badly pitted as a result of the dislodgement of the nonmetallic inclusions. The method, therefore, is not recommended when the correct preservation of the inclusions is essential to the purpose of the examination.

(2) *Grinding papers*, such as No. 0000 or 600 emery preserve the nonmetallic inclusions intact, but cause a considerable distortion of the surface metal and yield scratches of uneven depth, thus frequently retarding the final polish. Finer and more even scratches can be obtained by using a No. 000 or 600 paper which has been partly worn by use and glazed by polishing on it a piece of graphite.

(3) *Grinding with 600 emery on wax or paraffined cloth disks* preserves the nonmetallic inclusions quite well, yields fine, even scratches which are removed easily during the final polish and do not produce an excessive amount of disturbed metal. This method represents an excellent compromise between the two methods previously discussed.

(4) *Grinding with 600 or finer powders on lead laps* is probably the best method of rough finishing so far developed. The inclusions are well preserved, the specimen possesses a degree of flatness not attainable by any of the other methods, the scratches can be made fine and even by judicious selection of the powder and by carefully avoiding contamination with coarser grit, and it does not produce excessive distortion of the surface metal. This method, however, is applicable only to specimens which have been ground very flat during the prior stages, for otherwise the rounded parts of the specimen will not come in contact with the abrasive and consequently will not be acted upon.

The Final Polish—This step is generally carried out on a soft cloth with either levigated alumina, rouge, magnesia or other equally fine finishing powders. The selection of the finishing powder is a matter of individual preference, for equally good results can be obtained with any of them, provided they have been properly

levigated. The writer prefers alumina because it is the cleanest to handle and because an excellent grade can be purchased already levigated.

The type of cloth to use depends on the purpose for which the specimen is being prepared. If it is desired to obtain the best possible preservation of the nonmetallic inclusions, or the graphite flakes in cast iron, then it is advisable to use a hard, pileless fabric, such as the dull side of a heavy silk satin, or a good grade of heavy cotton or linen cloth, for it has been observed by many experienced metallographers that the softer materials, such as broadcloth or "kittens ear", exhibit a pronounced tendency to dislodge the inclusions. On the other hand, the soft fabrics are preferable when the structure of the specimen is to be examined or photographed at high magnification, for these fabrics produce fewer and smaller scratches.

It would be of little value to make precise recommendations as to the optimum speed to use for the final polish, because experience has shown that satisfactory results are possible at a wide range of speeds. However, the consensus of experienced metallographers is that best results are obtained at low speeds. At the author's laboratory a speed of 280 r.p.m. for a 9 in. disk is used.

Defects of Polished Surfaces—The defects most frequently found in metallographic specimens are: (1) Scratches, (2) rounding of the corners and edges of the specimen, (3) pits resulting from dislodgement of the nonmetallic inclusions, and (4) distortion of the surface metal.

(1) *The avoidance of scratches* is a question of cleanliness, and careful levigation of the finishing powder. Some of the most common causes of scratches are dirty hands, grit under the finger nails, abrasive from the previous operations on the sides of the specimen and contamination of the finishing fabric with flying grit from other wheels. The remedies suggest themselves; proper levigation of the finishing powder, careful washing of the specimen and hands, particularly before attempting to give it the final polish and keeping the wheels well covered when not in use.

(2) *The flatness of a specimen*, as was pointed out before, depends on the method of polishing and on how it is mounted.

(3) *The prevention of pits* resulting from dislodgement of the inclusions has already been discussed. It will be well to state here, however, that a pitted surface gives an exaggerated impression of the amount of "dirt" in the steel, and that as a result of improper polishing many a satisfactory heat of steel has been branded "too dirty". It is treading on dangerous ground to rate a steel as dirty unless one is sure that the inclusions are preserved intact.

(4) *Distortion of Surface*—Of all the defects of a polished surface, the most misleading, common and subtle is the inevitable distortion of the surface layer brought about when a malleable material is ground with a hard abrasive. It can be said without exaggerating that the greatest progress made in metallographic polishing during the last ten years, is the recognition of the existence of this distorted layer and its elimination by the method of alternate polishing and etching to be described. While some methods of polishing produce less distortion than others, the writer knows of none yielding an undistorted surface. It is well to assume, therefore, that the structure revealed by etching a highly polished surface is not the true or undistorted structure of the metal. The question now is, how can the true structure be revealed? The writer knows of no more dependable way of accomplishing this than the following: The polished surface is given a normal etch and its structure noted under the microscope using the dry objective of highest resolving power available. It is then repolished on the final wheel, reetched and reexamined. The process is repeated as long as changes in the appearance of the structure are noticed. As a rule two or three repolishes suffice, but occasionally, particularly when working with soft metals, more may be necessary. In general, the softer the metal the greater the distortion, but even hard metals are never polished completely free from distortion. Attempt to short cut the process by deep etching generally results in pitting and obliteration of the finest details of the structure.

Summary—The perfectly or ideally prepared specimen must possess at least the following characteristics: (1) It must be truly representative of the metal both as to chemical composition and physical condition. (2) It must be sufficiently flat, from edge to center, to permit examination at all points at all magnifications. (3) It

must be free from scratches, stains, and other imperfections which tend to mar its appearance. (4) It must contain intact all nonmetallic inclusions. (5) It must be free from all traces of disturbed metal.

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Photomicrography

By J. R. Vilella*

The purpose of photomicrography is twofold; to procure permanent and accurate records of structures which are finer than the unaided eye can see, and to show others what we saw with the aid of the microscope. To accomplish this satisfactorily a photomicrograph must meet certain minimum requirements: I. It must represent the true structure of the metal. II. Its magnification and resolution must be sufficient to show clearly all significant detail. III. It must be technically correct photographically.

I. The True Structure of a Metal—It is of the utmost importance in the preparation of metallographic specimens to bear in mind that the attainment of a specular finish free from scratches does not necessarily constitute a satisfactory polish for photomicrography. Frequently, the structure revealed by etching a highly polished surface is not the true structure of the metal but merely that of a layer of metal which has suffered considerable distortion as a result of polishing. The true or undistorted structure lies below this layer and will not be seen until all traces of distorted metal have been eliminated. As is to be expected, the softer the metal the deeper the distortion, but even hard metals are susceptible to this effect. It is well, therefore, to expect distortion in all polished surfaces and to make certain of its elimination before a photomicrograph is made. For a more detailed discussion of this subject see the article on Metallographic Polishing.

Likewise, a specimen is not ready to be photomicrographed until it has been correctly etched. Correct etching consists of (1) selecting the reagent best suited to the chemical composition and physical condition of the metal, and (2) etching to produce the proper degree of contrast, which depends on the element of the structure which is to be emphasized and on the magnification at which it is to be photographed. Obviously, an etched surface exhibiting stains, etching pits or uneven attack is not correctly etched.

What reagent to use is entirely a matter of experience. If any doubt exists, several of the reagents tabulated in the article on Etching Reagents should be tried and the photomicrograph made after etching with the reagent which most clearly reveals the true structure, for that is the best reagent for the specimen at hand.

The depth of etching, or degree of contrast produced in the structure is of great importance in photomicrography. While it is not possible to give a set of instructions covering all cases, observance of the following will be found helpful:

1. Etch no deeper than necessary to bring out the significant detail.
2. A degree of contrast satisfactory for low power photomicrography is generally excessive for the best possible definition of the structure at high magnification.
3. If high contrast is desired, it is preferable to obtain it by photographic means rather than by deep etching, for deep etching obliterates the fine details of the structure.
4. If a specimen is insufficiently etched (too low contrast) it is preferable to repolish on the finishing wheel and to re-etch, rather than to superimpose one etch on the other.
5. Do not touch an etched surface with anything, and photograph soon after etching.

II. Magnification and Resolution—Given a properly polished and etched specimen the first question to decide is the magnification and the objective to use in making the photomicrograph. There are two rules concerning magnification which are sound but not inflexible:

1. Photograph at the lowest magnification which shows clearly all significant detail.
2. To obtain from a given objective the maximum amount of detail (resolution) and the sharpest image, maintain the magnification between the limits of 400-1000 times the numerical aperture (N.A.) of the objective.

A magnification of at least 400 N.A. is needed by a person of normal vision to distinguish all the detail resolved by the objective. This magnification, however, barely renders visible the finest detail and consequently is not comfortable to look at. At higher magnification the detail becomes easier to see, but at the same time the image loses sharpness. It is necessary, therefore, to arrive at a compromise. It has been found through experience that 1000 N.A. is as high as it is possible to go and still have an image of acceptable sharpness when achromatic

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objectives are used. However, photomicrographs have been made with apochromatic objectives of the highest quality at better than 1500 N.A. which appeared acceptably sharp when viewed at a distance of 10 inches from the eye. It must be borne in mind, however, that to produce a sharp photomicrograph at even 1000 N.A. correct polishing and etching are essential, and all other causes of defective images must be absent.

A magnification in excess of 1000 N.A. necessarily involves a considerable degree of empty magnification but it is justified when the photomicrograph is to be viewed from a distance, as by several observers simultaneously.

Resolving power is the property of a lens which enables it to show distinctly separated two elements of the structure which lie close together, as for example, the lamellae of pearlite. The degree of fineness of detail which an objective can reveal, that is, its resolving power, increases directly with its numerical aperture, but the fact that an objective of high N.A. possesses high intrinsic resolving power does not necessarily mean that it will resolve a given fineness of detail under all conditions. It merely means that it will resolve that detail if properly used. It is important, therefore, to examine those factors under the control of the metallographer which affect the resolving power of an objective.

In the first place, the specimen must be correctly polished and etched for not even the objective of the highest N.A. will show clearly a structure in which the detail has been deformed or obliterated by poor polishing and etching. In addition the following factors must be considered: 1. Proper adjustment of the illuminating system. 2. Optimum opening of the aperture diaphragm. 3. Wave length of the light used. 4. Method employed to illuminate the specimen.

1. Proper adjustment of the illuminating system is essential because otherwise the image produced can be misleading. It is not possible, however, to make definite recommendations for the correct setting of the illuminating system owing to the varied design of the microscopes in use throughout the metal industry. It must suffice to say that failure to maintain the illuminating system adjusted in strict accordance with the instructions given by the manufacturer of the instrument invariably leads to some loss of resolving power.

2. Because the image produced by microscope objectives, particularly those of high N.A., is not always as flat as would be desirable, many resort to expediency of "stopping down" the aperture diaphragm of the microscope in an effort to secure a larger area in focus, a practice which is equivalent to cutting down the N.A. of the objective and therefore its resolving power. High power objectives cannot always be used at full aperture because of the interference of "flare," or internal reflections, but there is an optimum opening for every objective at which flare is not objectionable and which should be determined by the metallographer to enable him to use the objective at its highest practical resolving power. Lack of flatness of field can be partly remedied by the use of negative oculars designed specially for that purpose, but never at the sacrifice of resolution. A small field with maximum resolution is preferable to a large flat field lacking resolution.

3. The resolving power of an objective is higher the shorter the wave length of the light illuminating the structure. For maximum resolution, therefore, the shortest wave length for which the objective is adequately corrected should be used, that is, yellow-green for achromatic and blue-violet for apochromatic objectives. This is the principal function of light filters in ferrous metallography because the structures are seldom highly colored, but in nonferrous metallography, where brightly colored structures are not uncommon they are also used to bring about a more accurate tone rendition of the colors. Inasmuch as photographic emulsions are not equally sensitive to all colors, it is often necessary to filter out or partly suppress some of the wave lengths to which the emulsion is most sensitive in order to reproduce photographically the correct relative brightness of the colors.

4. Modern metallurgical microscopes are generally equipped with plane glass vertical illuminator, prism illuminator, dark field illuminator, polarized light, and with adjustments designed to produce the effect known as conical illumination. The plane glass vertical illuminator is the type generally used in photomicrography because it permits obtaining from the objective all its resolving power. In most microscopes it is placed in a fixed position at the factory and requires no further adjustment from the metallographer.

The prism illuminator is supplied for two purposes: As a means of obtaining oblique lighting and to provide brilliant illumination for dark structures, and for projection. Because they utilize only one half of the pencil of light, they cut the resolution of the objective in half, this loss of resolution occurring only in the direc-

tion at right angle to the edge of rotation of the prism. They are intended only for low power work.

Dark field illumination is characterized by the fact that a reflecting surface lying perpendicular to the axis of the objective and illuminated by converging rays reflects no light into the microscope and consequently appears dark. Any part of the structure which is not perpendicular to the axis of the objective reflects into the microscope some of the light which strikes it and appears brightly illuminated. This method of illumination has several distinct advantages over ordinary bright field illuminations: (1) Inasmuch as the objective is not used as a condenser, as is the case in bright field illumination, there is less "flare" or internal reflections and the objective can be used at full aperture; (2) extreme contrast (black and white) can be obtained when desired; (3) it permits the examination of surfaces which are not so highly polished as is necessary for bright field; (4) it frequently renders visible detail which either through lack of contrast with the surrounding material or through insufficient resolution cannot be seen under bright field illumination; and (5) colored structures are shown in their natural colors.

The use of reflected polarized light in metallography is discussed fully in another article in this Handbook.

Conical illumination is a means of illuminating the structure obliquely without sacrificing resolution, as happens when the prism illuminator is used for the same purpose. The relief it produces imparts to the image a natural appearance, serves to differentiate between parts of the structure which under axial illumination appear identical and makes fine detail easier to see. Conical illumination, if properly used, yields evenly illuminated photomicrographs of high resolution and very pleasing to the eye.

Most microscopes are provided with a second iris diaphragm known as the illuminated field diaphragm, which is so placed in the microscope that its image is focused on the surface of the specimen when the specimen is in focus. Because of its position, this iris does not affect the resolving power of the objective, but it will be observed that as it is closed down the fully illuminated field becomes smaller and the contrast and sharpness of the structure improves perceptibly. For photomicrography, whenever the size of the illuminated field is larger than the plate or film, the iris should be closed down until the diameter of the fully illuminated image is equal, or less, than the diagonal of the photographic plate. This is especially important in high power photomicrography.

III. Photographic Technique—For a photomicrograph to accomplish its purpose it must show the structure with sufficient clearness to convince the observer that it is a faithful reproduction of the structure. A photomicrograph which because of technical imperfections lacks clearness, generally defeats its purpose and serves to cast doubts rather than to convince the observer.

The photographic plates or films best suited for photomicrography are those possessing the following characteristics:

1. High sensitivity to yellow and green light, that is, they must be orthochromatic. (All emulsions are sensitive to blue light; only panchromatic emulsions are sensitive to red light.)
2. Sufficient exposure latitude to yield properly exposed negatives without the necessity of close estimation of the exposure time. This is necessary because the intensity of the arc light generally used in photomicrography fluctuates considerably even while the exposure is being made and because the reflectivity of the various parts of the structure vary widely depending on their polish, composition and degree of etching.
3. A fine grain emulsion so that it can record accurately extremely fine details. (Photographic emulsions also possess "resolving power"; in general, the finer the grain the smaller the detail which can be recorded in a photograph.)
4. An effective antihalation backing is also important since the latitude over which the emulsion can reproduce accurately the finest details will be considerably shortened by the presence of halation.

The correct exposure is that which places the brightest and darkest portion of the structure within the limits of the latitude of the emulsion; that is, the brightest parts are not over exposed nor the darkest under exposed. Considering that the emulsions used in photomicrography are of the "short scale" type, it can be readily seen that the greater the degree of contrast produced by etching the more accurate the exposure needs to be. Indeed, it occasionally happens that the contrast produced in the structure through over etching is so great that even though it can be encompassed within the latitude of the negative, it exceeds that of the printing paper which is always less, and therefore a good print cannot be made. After all,

a negative is only a means to an end, that being the achievement of a perfect print. It is for these reasons that care should be taken to avoid etching with excessive contrast.

Whenever there is doubt as to the correct exposure, an exposure test can be made as follows: The entire plate is given an exposure estimated to be somewhat on the short side, let us say 2 seconds, and then the dark slide is pushed in approximately one inch and another exposure made of the same duration. The slide is then pushed in another inch and exposed again, but this time for 4 seconds, and the process repeated until a set of exposures, each double the preceding one, is obtained.

It helps to secure negatives of uniform quality from day to day to standardize the developing practice. The time temperature method (tank development) lends itself to standardization better than the tray or inspection method, and should be preferred. The developer recommended by the manufacturer should always be used. The length of time that a plate should be developed depends on the degree of contrast desired, for contrast increases with the developing time, provided that the temperature and agitation are constant.

Proper fixing and washing are also important. An active fixing bath containing an effective hardener is sufficient, provided that the temperature of the bath does not exceed 75°F. Above this temperature there is danger of the emulsion softening and reticulating. To prevent this in hot weather, it is advisable to use a "short stop" hardening bath consisting of 2% chrome alum and 2% sodium bisulphite. The hardener should be freshly prepared and used between development and fixing, leaving the plate in it for 3-5 minutes with the light off. The negative should then be fixed for at least twice the time required to clear it and washed in running water for 30-60 minutes. Insufficiently washed negatives deteriorate in a short time.

Correct printing in photomicrography consists of reproducing on photographic paper all the detail that the negative was able to grasp and in reproducing this detail in the proper tone relations. It consists essentially of two operations: (1) Choosing the grade of paper to fit the contrast of the negative, and (2) choosing the exposure which will print through the densest part of the negative which must show detail. To accomplish this, photographic papers are available in several grades of contrast. The low contrast or "soft" papers are for use with high contrast negatives and the "hard" or contrasty papers with "flat" or soft negatives. While these various grades can be obtained in a variety of surfaces the glossy finish is generally used in photomicrography because the smoother the surface the larger the scale of contrast reproduced by a photographic paper.

Summary—All that can be done in photomicrography is to reproduce the significant detail and tones of the structure as faithfully as possible. This can be accomplished as follows: (1) By polishing the specimen in such a manner that the true structure will appear on etching. (2) By etching to a depth or degree of contrast that does not obliterate detail and can be reproduced photographically. (3) By adjusting the microscope correctly so that maximum resolution may be obtained. (4) By an exposure which produces an image within the latitude of the plate or film. (5) By the development of this image to a contrast that fits the scale of the printing paper. (6) By the use of a paper that has the longest possible contrast range.

For photomicrographic illustrations and a more detailed discussion of the various points emphasized in this article, see the A.S.M. publication "Metallographic Technique for Steel" by J. R. Vilella.

Radiography of Metals

By Kent R. Van Horn†

Introduction—X-rays are a form of radiant energy or electromagnetic waves which were first detected by Roentgen in 1895, and are frequently called Roentgen rays in honor of the discoverer. The latter name is used in Germany, while the term X-ray is more prevalent in France, England, and the United States. The X-rays are similar in many respects to light and other radiation of the electromagnetic spectrum in that they travel in straight lines, traverse through space without transference or intervention of matter, affect a photographic film, and are not influenced by either electrical or magnetic fields. The various electromagnetic vibrations differ essentially in wave length, the gamma rays emitted during the disintegration of radio-active elements are the shortest,* then the X-rays, followed by the ultra-violet, the visible, infra-red or heat rays, television, radio, and finally the extremely long waves of electricity. The shorter wave lengths are generally less absorbed by matter and are consequently more penetrating. Gamma rays emanating from radium or its associates having a wave length of from 0.005-1.4 Å (1 Å = 10^{-8} cm.), and X-rays ranging from 0.06-1019 Å penetrate material which is opaque to visible light having a wave length of from 3800-7700 Å.

Light is transmitted through different types of glass with varying degrees of ease. Similarly, X-radiation is absorbed differently by various substances of greater or less density, that is, all materials do not possess the same degree of X-ray transparency. The absorption coefficient of X-rays is roughly proportional to the density of the absorbing medium. (More precisely, the absorption co-efficient increases with the atomic number of the absorbing atoms, the number of atoms per unit volume and the X-ray wave length.) Consequently a sound section of steel will absorb more radiation than a similar section of aluminum or organic tissue. It is possible, therefore, to locate inclusions differing appreciably in density from the surrounding material. These relations are the basis of the expanding science of radiography which may be defined as the nondestructive testing of matter with radiant energy (either X or gamma rays). The experimental procedure consists of passing radiation through the specimen and detecting the various intensities of the emergent beam by a photographic film or fluoroscope screen. The film is used for metals, while the fluoroscope is frequently employed in the examination of nonmetallics.

Probably the first practical application of X-rays was radiography, and today it is an invaluable test for medical and industrial diagnosticians. In 1922, 200 kilovolt peak, 8 m.a. X-ray tubes were available which could penetrate three and one-half inches of cast steel. This has been increased to five and one-half inches of rolled steel with 400 kilovolt peak, 5 m.a. apparatus in 1938. Reasonable quantities of the shorter wave length gamma rays can penetrate ten inches of steel. The present article will be confined to X-ray radiography. However, much of the individual discussion of general technique and interpretation apply to the gamma ray.

Generation of X-Rays, and Apparatus—It is known that X-rays are produced when matter is bombarded by a rapidly moving stream of negatively charged particles (electrons), that is, when the electrons are suddenly stopped by matter. A part of the kinetic energy is converted to energy of radiation (X-rays). In addition, the absorption of X-rays by various materials is accompanied by the emission of secondary radiation.

The essential conditions¹ for the generation of X-rays are: (1) Source of electrons (cathode rays) proceeding toward the target; (2) a target (anode) located in the path of the cathode rays; (3) a means of applying a potential difference between the cathode and the target which will give the requisite velocity to the electrons during the passage of the intervening space so that when they bombard the target the necessary X-rays will be propagated.

The first two requirements are incorporated in the X-ray tube which may be of two types. The first is a gas (ion) tube where the source of electrons is a mass of rarified gas that is ionized. The second (electron) type is a highly evacuated glass bulb or cylinder containing one or, in special tubes, two tungsten wire

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*The cosmic rays have a shorter wave length than the gamma rays but their nature is controversial as they may be electro-magnetic waves or electrically charged or neutral particles.

filaments which emit the cathode rays and either a button, solid, or hollow target. The electron type is universal for industrial radiography and may range in capacity from 85-400 kilovolt peak. The lower voltage tubes have a fine focus and are generally air cooled while water or oil cooling and larger focal areas are characteristic of 300-400 kilovolt peak tubes. Radiographic tubes may or may not be self rectifying.

The third condition, a difference in potential, for the original apparatus was obtained by a direct current electrostatic generator, while later the ideal but expensive and dangerous source, a storage battery was utilized. However, today the high tension a.c. closed core transformer is used for industrial installations. Accessory equipment for the transformer type of power consists of: (1) An auto transformer for the control of the high tension transformer input; (2) a means of current rectification from a.c. to d.c., either valve tube or mechanical type (the valve tubes are replacing the older mechanical type); some of the recent installations are equipped with the newly developed self rectifying tubes and therefore do not require d.c. current; (3) a device for regulating tube current; (4) separate transformers for supplying the filament current of the X-ray and valve tubes. Additional windings on the high tension transformer or insulated storage batteries are also satisfactory as a filament supply; (5) instruments for measuring voltage such as a calibrated primary transformer voltmeter, electrostatic voltmeter, sphere gap, or spectrometer.

The radiographic units may be classed according to portability: (A) Permanent type where the location of the apparatus is fixed; (B) portable type of equipment that may be moved throughout the plant with comparative ease. The more recent installations are generally portable and are compact. Thus a complete oil immersed 300 kilovolt peak, 10 m.a. power plant and X-ray tube can be contained in a shock proof case 6 x 4 x 4 ft. suspended on trunnions on a movable truck.

It is imperative to protect the operators or any persons in the vicinity of all types of apparatus from both primary or secondary X-radiation because of the injurious effects. This may be accomplished by adequate thicknesses of dense materials which are impervious to X-rays, such as lead and concrete or fencing off a generous area around the temporary location of a portable set.

Methods of Detecting X-Rays—X-rays are detected by their effects on matter, which may be visible and either temporary or permanent. In addition, X-rays are revealed by induced physical and chemical changes which may be made permanent. Thus X-rays have been detected by an ionization chamber, fluorescent screen, photographic film, plate, or paper. Inasmuch as the film is generally used for industrial radiography, the other methods will be only briefly mentioned.

Vapors and gases such as SO_2 , ethyl bromide, and methyl iodide are readily dissociated by X-rays but difficulties are encountered in measuring only the ionization and not secondary effects. Tedious manipulation is required, and further, the average intensity over an entire region is measured which is not indicative of the variations from point to point. An ionizable chamber would be unsuitable for revealing small defects in large castings.

The visible fluorescence excited by X-rays on screens of calcium tungstate, or barium platino-cyanide, is utilized for medical examination, but only to a limited extent for the inspection of metals. Fluorescent screens vary in the brilliancy (glow) corresponding to different degrees of transparency of the exposed object, so that the dense structures causing less glow appear darker, which is the reverse of the effect on the photographic film. The fluoroscope offers the advantages of speed and economy but unfortunately does not integrate X-ray energy as does a film emulsion, and therefore much larger quantities of radiation are required to penetrate the same specimen. Furthermore, the record is temporary and the sensitivity is very inferior, ranging from $\frac{1}{5}$ - $\frac{1}{10}$ of that of a film.

An X-ray paper is marketed which costs about one-half that of a film and differs in several significant characteristics. The contrast of the paper is 40% less than the film, and the range of useful densities (latitude) is also materially less because of the reflection of some light from the surface. However, X-ray paper may be satisfactory for special cases, as the examination of a large number of similar parts where previous tests with films had indicated that objectionable defects would be adequately disclosed.

X and gamma rays, similar to light, produce a latent image on a photographic emulsion which is permanent and reproducible. Films designed especially for X-ray service consist of two thick sensitive layers, separated by a cellulose acetate

base that is, dupletized, and have more contrast than a single emulsion. (Photographic plates are not used because of inconvenience and their inability to be satisfactorily dupletized.) The image registered on the negative is dependent on the variations in absorption of the X-rays by the object and on the characteristics of the silver bromide emulsion. The important qualities of films are contrast, latitude, and speed. As the exposures for industrial radiography are relatively long, compared to medical work, the speed encountered in the films of today does not vary sufficiently to warrant consideration. The radiographic sensitivity (the minimum variation in thickness, or density detectable in a specimen) is the greatest with high contrast emulsions. However, with maximum differentiation of detail (contrast), the range of useful film intensities (latitude) is diminished. In other words, a high contrast emulsion will reveal minute defects in a certain section but would sacrifice satisfactory exposure of regions of appreciably greater or less thickness. Sufficient latitude will allow for unavoidable variations in exposure and development, also reasonable differences in thickness. Generally, emulsions that possess a compromise of contrast and latitude are desirable, although for some conditions requiring extraordinary sensitivity, high contrast may be selected.

Films are developed and fixed by the tank method in X-ray solutions designed to give extreme contrast and negligible chemical fog. The contrast³ is sensibly maximum from 5-9 min. development in standard X-ray solutions at 65°F. As the density (film blackening) increases with developing time, the exposure may be reduced by prolonging the latter. Thus with an 8 min. development, the exposure time may be decreased by 30% of that required for a 5 min. developing period.

Accessory Equipment—Negatives should be viewed for interpretation with a source of diffuse illumination which will reveal detail in areas of extreme blackening. The density of the film does not affect the visual sensitivity with a variation in illumination ranging from 5-3000 ft. candles. About 1000 ft. candles are recommended; this is obtained with either the 200 or 250 watt blue or argon lamps that are supplied in the commercial illuminators.

Film blackening may be precisely measured by a microphotometer. A density difference of 2% is considered the standard minimum value of detection. The usable densities range from 0.4-1.5 (standard density scale units), but detail is perceptible as high as 2.0. A film density of 0.7 frequently serves as a relative standard for comparing technique.

Improvement in contrast and a decided reduction of exposure time can be obtained by employing intensifying screens. A screen consists of an intensifying compound, usually calcium tungstate and infrequently zinc silicate, or zinc sulphide or barium platino-cyanide, coated with a cellulose binder on a cardboard support. On exposure of calcium tungstate or similar material to X or gamma rays, a visible and blue-light are emitted to which a film emulsion is highly sensitive, thereby accelerating the exposure effect. Two screens, one in front and the other behind the film, are generally used, although superior definition but less speed is procured with only one. Thick calcium tungstate layers are more efficient³ than thin, while the back screen may be even thicker than the front but not to the extent where its own light will be absorbed. The particle size of the calcium tungstate is also critical, as coarse grains increase the speed, while fine grains are more conducive to sharpness (definition). Intensifying screens maintained at low temperatures are extremely fast,⁴ as exposures at 40°F. are 33% less than at 70°F.

Zinc sulphide has recently been investigated because the speed with exposures below 100 kilovolt peak is greater than that of calcium tungstate (about twice as fast at 40 kilovolt peak).

Metal foils, particularly lead, and sometimes copper or aluminum, slightly decrease the exposure period and improve the quality of the negative. A lead foil filter (about 0.005 in. thick) placed on each side of the film will reduce fogging by absorbing some of the secondary radiation. The definition is also enhanced by the resulting fine grained image.

Intensifying screens must be handled carefully as they are brittle, expensive, and scratch easily. Dirt or blemishes on the sensitive surface are readily recorded on the negatives and complicate the interpretation.

The speed of the various materials may be compared by their intensifying factors, that is, ratio of exposure without screens to that with screens for a radiograph of standard density developed under normal conditions. The intensifying factor² of calcium tungstate is about 100 with 150 kilovolt peak X-rays and 2 for

gamma rays. The ratio for lead foil ranges from 2-6 between 100-200 kilovolt peak.

Sensitivity of Radiography and General Technique—The minimum perceptible variation in density (sensitivity) within a specimen is a measure of the over-all accuracy of the radiographic method. The sensitivity may be expressed as the smallest thickness of discontinuity (defect) in inches that is revealed on the radiograph or as the percentage of the total thickness examined which the smallest defect detectable represents. Of the factors that affect sensitivity, some may be controlled, while others are permanent limitations imposed by the apparatus. A discussion of the variables will indicate a general preferred technique although the details such as the specimen arrangement, exposure time,* or film processing should be obtained from the literature references.

The type of target of the X-ray tube, the material supporting the target, the size of the focal spot, and the method of rectification influence the sensitivity and cannot be altered.⁵ The higher the atomic number of the target metal, the more penetrating (shorter) the wave length of the X-rays although this is accompanied by decreased contrast. If the target is not solid metal but a button imbedded in a supporting conductive metal, extraneous radiation of different wave lengths may also be emanated from the surrounding metal which may approach 10% of the total if not removed by filtering. The focus of the X-ray tube is not a point source but occupies a fixed area. Consequently, the smaller the focal area the better the definition and the less the distortion. Rectification units of the same peak kilovolt capacity have dissimilar wave length distributions (mean voltages), thereby generating different proportions of long and short wave lengths which affect the quality of the beam.

Among the important factors affecting sensitivity which can be regulated is the quality of the radiant energy. The radiation emitted from the tungsten target tubes, which are generally used, varies over a considerable range of wave lengths (quality) and is related to the voltage applied to the tube. As the potential increases from about 89-200 kilovolt peak the wave length of maximum intensity decreases from 0.138-0.062A with a corresponding reduction in contrast and sensitivity.⁶ The smallest detectable difference in density has been demonstrated⁴ to be a straight line function of the voltage when plotted on a semilogarithmic scale. However, the shorter wave length X-rays are required for the penetration of 2-5½ in. of steel. Consequently, it is desirable to employ the lowest potential which will penetrate a certain thickness in a reasonable period of exposure.

The sensitivity is dependent on the wave length of the X-rays and the nature of the exposed matter excluding the fogging effect produced by scattered (secondary) radiation. Secondary radiation consists of primary X-rays that are scattered through wide angles with no change in wave length and X-rays of longer wave length characteristic of the absorbing substance generated by ejected electrons. The quantity of secondary radiation increases with the applied voltage⁶ and the number of atoms encountered (thickness of the material). The secondary energy derived from the specimen and surrounding objects fogs the film, thereby diminishing the sensitivity. Fortunately this may be materially reduced by the use of Potter Bucky diaphragms,[†] lead or copper screens, and an increased exposure time.

Additional undesirable radiation causing fogging, but primary in nature, is that proceeding directly from the X-ray tube to the film without passing through the object. This can be eliminated by shielding technique, that is, placing lead shot and sheet or heavy (barium) plastic clay around the specimen so that there will be no portion of the film exposed directly to radiation. Suitable shielding or immersion in dense solutions** may be used to compensate for variations in sectional thickness or surface inequalities.

In the preceding section, criteria were described for procuring maximum sensitivity from accessory equipment, namely high contrast films and the proper type of intensifying screens.

*Exposure charts for various thicknesses of metals under different conditions are available.¹⁴ However, this data will not apply to all apparatus because of the difficulty in reproducing radiation with a pulsating potential and variations in films or screens.

†An industrial movable grid diaphragm has produced remarkable results with a 5 in. thickness of steel but requires a longer exposure time than normal.

**Various aqueous solutions of lead nitrate or acetate and ethylene iodide for steel, carbon tetrachloride or barium chloride for aluminum.

The geometrical relations of the focus of the X-ray tube to the film, the location, the size and orientation of defects also influence the sensitivity of radiography. Although the focal area is permanent, definition can be improved by increasing the tube-to-film distance. The greater the distance, the smaller the angle of exposure and the better the definition or sharpness. This relation is limited because of the corresponding increase in exposure time since the intensity of X or gamma rays, similar to light, decreases inversely as the square of the distance from the source of emission. Also, as the source approaches the film, the exposure angle is enlarged, which induces a nonuniformity of film density. It is therefore desirable to use the largest tube-to-film distance consistent with a reasonable exposure period.

Flaws may occur in any part of the specimen and may be oriented at any angle to the incident X-rays. As the defect-to-film distance is increased, or the diameter of the defect is decreased below 1 in., the actual sensitivity is proportionately diminished.⁷ Consequently, if imperfections are more likely to exist in a certain section of a casting, this location should be placed adjacent to the film during examination. The orientation of minute cracks, cavities or gross films is important and may necessitate several exposures at different angles so that cracks presenting too small a variation in thickness or composition for detection in one direction may be revealed in another where the path of the X-rays coincides approximately with its longitudinal axis.

It follows from the discussion of the various factors that the best sensitivity will result from employing a small focus tube, as low a voltage as possible, large tube-to-film distance, high contrast film exposed with intensifying screens with the scattered radiation and chemical fogging reduced to a minimum. Sensitivity data are available and indicate the limits that may be obtained parallel to the path of the X-radiation. The smallest detectable difference in thickness in inches for $\frac{1}{8}$ and 1 in. of steel was found⁷ to be 0.0039 and 0.0041 in. at 150 kilovolt peak, while at 200 kilovolt peak the values were 0.0049, 0.0052, 0.0057, and 0.0063 in. for $\frac{1}{8}$, 1, 1 $\frac{1}{2}$, and 2 in. of steel, respectively. The measurements illustrate the advantage of a lower voltage and the latter (200 kilovolt peak) when converted to per cent sensitivity range from 0.65% for $\frac{1}{8}$ in. to 0.31% for 2 in. of steel. A sensitivity of 0.41%, with 150 kilovolt peak is possible for 1 in. of steel, with laboratory precautions, although in industrial practice (higher potential) 0.8 to 1% is easily attained. Similarly a laboratory value for 2 in. of steel is 0.31%, while routine inspection should not exceed 1-1 $\frac{1}{2}$ %, and for 3 to 5 in. of steel at least 2% is expected. The significance of these results is that variations of composition or thickness causing less change in film density than the per cent sensitivity for a certain thickness will probably escape detection.

Interpretation of Radiographs—A radiograph is a shadow picture of material more or less transparent to radiation. The X-rays darken the film so that regions of lower density which readily permit penetration appear dark on the negative in comparison with areas of higher density which absorb more of the radiation. Thus, voids and cavities in metals are recorded as darker areas whereas heavy inclusions, such as iron scale or copper segregation in an aluminum alloy, register as a corresponding lighter region on the radiograph. The film therefore discloses conditions within the metal of different density or X-ray absorption which may be more or less than the surrounding material. The sensitivity values indicate the smallest variation in absorption that can be appreciated.

In the metal industry most of the radiographic installations are located in the foundry and the welding shop. Consequently, the general appearance on the radiograph of the familiar defects encountered in castings or welds will be described. In castings, differences in thickness due to the form and intentional cavities, as cored holes, are regions of low density and are revealed as darkened areas. Specimens containing variations in thickness caused by the unintentional absence of metal are also more transparent, resulting in darkening of the film. Excess metal and inclusions more dense than the base metal appear as light regions. The common casting defects of the latter two types may be recognized on the negative by the following characteristics:

1. Surface roughness appears as white or dark irregular areas with a smooth contour. The coloration depends on whether the surface protrudes or is depressed. The surface irregularities of a rough casting must be compared carefully with the radiograph and identified before an attempt is made to interpret the internal discontinuities.
2. Gas cavities, blow holes, and minute pinhole gas porosity appear as well defined spherical or rounded darkened areas.

3. Shrinkage, pipe and shrinkage porosity are represented by filamentary or dendritic dark regions of irregular dimensions and indistinct outline.

4. Misruns and cold shuts appear as very prominent darkened areas of variable dimensions with definite, smooth outlines where the metal failed to fill or unite completely before solidification.

5. Cracks are represented by darkened lines of variable width and are filamentary when derived from insufficient feeding or contraction (shrinkage) on cooling from the melt. Cracks originating from internal stress in solid metal are either angular or straight and are of more constant width.

6. Sand inclusions occur as gray to black spots of an uneven or granular texture with indistinct extremities.

7. Inclusions such as foreign material, segregation, oxide, and slag, in steel castings generally appear as dark regions of definite and smooth outline. In light alloy castings, copper or iron segregation and foreign matter of greater density than the base metal occur as well defined, white (opaque to the X-ray) areas.

The radiography of steel welds is confined primarily to boilers, pressure vessels, and pipe. The origin and interpretation of flaws have been exhaustively studied during the standardization of inspection methods, and a comprehensive survey is available.⁹ The defects in order of prevalence of occurrence in steel welds are: (1) Slag inclusions; (2) porosity; (3) cracks; (4) incomplete fusion between the weld and base metal or between two layers of weld metal. All the imperfections are less dense than steel and are recorded as darkened regions on the radiograph. With the exception of incomplete fusion which is represented by a dark line parallel to the scarf, of rather constant width and direction, the defects appear similar to their description for sand castings.

Radiographic Applications—In the metal industries, radiography has been largely restricted to the inspection of cast or welded products. The examination of worked metal such as forged, rolled, or drawn sections is very limited because of the uniformly dense structure and unlikely existence of flaws of sufficient size to cause a perceptible variation in film density. However, some forgings have revealed internal cracks, laminations, and inclusions, but the occurrence is too infrequent to warrant serious consideration of X-ray inspection. Therefore, the commercial value of radiography depends on the class of material to be tested. Apparatus has been installed in four types of organizations: (1) Manufacturers of boilers or pressure vessels and pipe for the testing of welds; (2) foundries for the inspection of castings and ingots; (3) army arsenals, navy ship yards, consulting laboratories, and universities for the examination of castings, welds, and miscellaneous products; (4) companies fabricating miscellaneous nonmetallic products.

The first (see Watertown Arsenal below) exclusively foundry radiographic equipment was installed in this country in 1927¹⁰ and each year has added to the list of casting companies who have discovered X-ray methods to be indispensable. Apparatus now exists in cast or alloy iron, steel, and light alloy foundries, and is primarily used (75%) for the development of casting technique and to a smaller extent for routine inspection. After a successful procedure has been established only occasional X-ray confirmation is necessary. This division of the work is natural because of the added cost of radiography. However, complete examination is warranted for highly stressed castings such as pipe valves or fittings for high pressure-temperature systems, heat resisting retorts, airplane crank cases, or shock absorbers. An outstanding application was the nondestructive testing of all pipe, fittings, and turbine shells for a 1200-lb. steam line of a large electric power plant.¹¹ After several years of service, no casting has failed although a considerable number were originally rejected because of the X-ray specifications. Frequently, when the production of a part is too small to justify the expense of a forging die and operation, castings determined by the X-ray inspection to be homogeneous and sound have been acceptable. A manufacturer has appreciably increased the service life of heat resisting furnace fittings, pots, retorts, and thermal protection tubes by radiographic researches.¹² Some indication of the value of radiography to this producer is that 2,000,000 sq. in. of film were exposed in the year 1937.

The ability of the X-ray to disclose the injurious defects in welds such as slag inclusions and porosity has been recognized by the Bureau of Engineering of the Navy, the A.S.M.E., and the American Petroleum Inst. In 1931, the A.S.M.E. Class I Boiler Code governing boiler drums and unfired pressure vessels permitted welded construction but required complete X-ray inspection of the seams. Welded construction of pressure equipment has progressed phenomenally since 1931, although little utilized previously because an efficient nondestructive test had not been available. Also, it is doubtful if the fusion welded structural developments

would have attained the popularity enjoyed today without the confidence reflected by the acceptance of welded boilers.

The impetus from the boiler industry, since 1931, has rapidly advanced the use of radiography so that there are now probably 5 welding installations for every foundry unit. In 1938, there were about 57 equipments distributed among 34 manufacturers and consumers of boilers and pressure drums. The six major companies, engaged in fabrication of pressure apparatus,¹³ have examined over 7,000 vessels representing approximately 161 linear miles of welded steel joints ranging in thickness from $\frac{1}{4}$ -5 in. All fusion welding of the penstocks of the power plant at Boulder Dam, totaling 21.6 miles of seam, was minutely inspected. This project alone required about 77,000 exposures consuming 1,500,000 sq.in. of film. Unlike the foundry, the majority of weld radiography is devoted to routine testing while a smaller portion is confined to the development of technique.

U. S. Army officials, visualizing the possibilities, installed the first equipment in this country for the radiography of cast and welded products in 1922 at Watertown Arsenal, Mass.¹¹ This was followed by apparatus at Rock Island Arsenal, Ill., and also interested other governmental divisions. The consulting laboratories¹⁴ and some universities have materially aided in the developing of X-ray technique and introducing new applications. The experience of these organizations include: Castings, welds, and nonmetallics.

The capacity of the X-ray to reveal variations in density has resulted in a number of interesting nonmetallic applications.¹⁵ Briefly, oil paintings have been radiographed to determine their origin or genuineness by art museums. Bakelite molds, candy, coal, carbon contacts, golf balls, rubber tires, tobacco, and tooth paste have been examined to detect foreign material or flaws. Many nontransparent assemblies such as broadcasting tubes, insulated wires, and closed cores are inspected to ascertain correct alignment of the internal components.

Gamma Ray Radiography—Gamma rays emanating from the disintegration of radio-active elements have experienced limited radiographic applications. The source may be radium, radon, or mesothorium, which emit considerably shorter and more penetrating wave length radiation than that of X-rays. It is estimated that the gamma wave length spectrum corresponds to X-rays that would be generated by potential of from 400,000 to 1,500,000 volts.

In addition, the gamma radiation differs from the X-rays in several pertinent qualities. As contrast diminishes with decreasing wave length or increasing voltage, the gamma rays are unable to reveal the very small defects in $\frac{1}{2}$ to 2 in. of steel. The gamma ray wave lengths are characteristic of the source and cannot be regulated for contrast or variable thickness. An advantage of the gamma radiation which improves the sensitivity is the small absorption and low scattering power resulting in appreciably less fogging than that produced by X-rays. The net effect of the two compensating factors, lack of scattering and low contrast, is that the sensitivity of the gamma ray is inferior to the X-ray for steel sections $\frac{1}{2}$ to 3 in. thick. The per cent sensitivity of gamma rays under laboratory conditions for $\frac{1}{2}$ -2 in. of steel ranges from 5-1.75% and for 3-6 in. is 1.3%.¹⁵

Other important considerations which limit extensive use of gamma ray radiography are the expense and time of testing. The rental or purchase of only a small quantity of radium is feasible which would require exposure of the order of 10-16 hr. to penetrate steel sections 2-5 $\frac{1}{2}$ in. thick. Although gamma rays are not directional but are emanated spherically so that many specimens may be simultaneously examined by suitable distribution about the source, the number of exposures for a specific time is relatively small compared to the large number that could be obtained with the X-ray in the same period.

The gamma radiation is attractive for applications where good definition, absence of apparatus and ease of arranging exposures are desired. (The technique has been developed and the details are described.^{15, 16}) Excellent definition can be procured by decreasing the dimensions of the source, that is, by reducing the quantity of radium or absorption of radon by a small piece of carbon. The simplicity of gamma ray technique is utilized for the radiography of steel castings and welded structures in an assembly or in service, inaccessible to X-ray apparatus. Frequently circumferential welds of pipe in a line are more economically examined by gamma radiation because of the number of films that may be simultaneously exposed from a single radio-active source and the inconvenience of moving or orienting the pipe for X-ray inspection. Also, companies not having sufficient nondestructive testing to justify an expenditure for an X-ray installation, rent radium occasionally. It

would seem that the gamma rays will not be used as extensively for industrial radiography as X-radiation but will be confined primarily to the examination of material opaque to the X-ray ($5\frac{1}{2}$ -10 in. of steel), inaccessible or inconvenient to the latter type of radiation. The two methods do not appear to be competitive but supplement each other.

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X-Ray Diffraction

By Charles S. Barrett*

Introduction—A wealth of information on the structure of matter has resulted from the discovery of von Laue and his collaborators in 1912 that crystals act as suitable gratings for diffracting X-rays. The regular repetition of identical groups of atoms throughout a crystal forms a three dimensional grating which affects a beam of X-rays in much the same way that an optical grating affects a light beam. The repeating unit in a crystal, the unit cell, is a few Angströms in each dimension and is thus able to form a diffraction spectrum of X-rays which have a wave length of one or two Angströms. By directing a small beam of X-rays at a small sample of a substance and photographing the rays diffracted in different directions from it, the substance can be classified as amorphous, crystalline, or intermediate; the perfection of the crystal lattice can be determined; single crystals can be distinguished from polycrystalline substances, and the size of crystallites can be approximately determined; from the X-ray pictures supplemented by other data the crystal can be assigned its proper classification among the 7 crystal systems, the 14 space lattices (Bravais lattices), and the 32 point groups (symmetry classes), and the 230 space groups, and the positions in the unit cell of all atoms can be accurately determined, barring experimental difficulties or highly complex crystal structures. Additional information that can be read from the photograph includes the orientation of a single crystal and the preferred orientations in a polycrystalline specimen, the dimensions of the unit cell to a high degree of precision, qualitative and in some cases quantitative information on the intensity of internal or applied stresses, the effect of plastic deformation, of heat treatments, or of the mechanism of deposition, crystallization, transformation and precipitation on the lattice, and the constitution of organic and inorganic systems, minerals, and alloy systems.

The interpretation of the diffraction effects has been greatly simplified by a principle discovered in 1912 by W. L. Bragg. He pointed out that each of the diffracted rays could be interpreted as a *reflection* of the incident X-ray beam from a plane of atoms within the crystal. Given a parallel set of such planes of atoms repeating throughout the crystal and spaced at intervals of d , the condition for X-ray reflection from these planes is

$$n\lambda = 2d \sin \theta$$

where λ is the wave length of the X-rays, measured in the same units as d , n is the order of the reflection (always an integer), and θ is the angle of incidence of the beam on the planes, which is equal to the angle of reflection from the planes. This relation between the spacing of atomic planes, the wave length, and the diffraction angle, known as Bragg's law, and the optical reflection analogy on which it rests is the basis for interpreting almost all practical applications of X-ray diffraction.

Description of Apparatus for Typical Installation—X-ray diffraction installations are simpler than radiographic installations: They operate at a lower voltage, generally 30,000-60,000 volts; rectification of the high voltage is optional, and condensers and other filtering equipment to produce constant voltage direct current are unnecessary. Usually included in the installations are suitable overload relays, safety devices, switches, and meters for reading voltage and the current through the X-ray tube.

Both gas tubes and electron tubes are in common use, gas (or "ion") tubes operating at a critical gas pressure of about 0.01 mm. of mercury, with a cold cathode, and electron tubes operating at a high vacuum with a hot filament (usually a tungsten spiral). Tubes of both types may be made demountable so that targets of various elements can be interchanged at will and cathodes replaced when necessary. Electron tubes made of glass, highly evacuated and sealed off from the vacuum pumps, are widely sold. The sealed-off molybdenum target tubes are the nearest approach to a universal tube for commercial applications, for both monochromatic (characteristic) radiation and a considerable quantity of polychromatic (general) radiation is emitted, so that the tube can be used with fair success with nearly all methods. Sealed-off tubes require the minimum amount of

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attention and skill in operating, but demountable tubes have the maximum flexibility and are required in many advanced research problems and in work of high precision. Gas tubes are preferable for work with powder methods because of the purity of the radiation. In electron tubes tungsten is slowly deposited on the target, and with improper vacuum technique mercury is also deposited, so that the pure spectrum of the target material may become contaminated with radiation from tungsten and mercury.

Complete units with tubes, transformers, and controls fully enclosed may be purchased from manufacturers. These permit from 2 to 12 cameras to operate simultaneously, and usually are supplied with sealed-off tubes having molybdenum targets. Demountable tubes of various types and many varieties of cameras may also be purchased. Exposures require varying lengths of time depending on conditions, usually between an hour and a day; zinc sulphide intensifying screens placed in contact with the film will reduce exposure times materially.

Laue Method^{1,2}—The Laue method uses a beam of X-rays containing many wave lengths. A system of pinholes confines a beam to a narrow pencil of rays which falls upon a small crystal or penetrates a thin crystal. The usual arrangement is for a photographic plate to be placed 4 or 5 cm. beyond the crystal and perpendicular to the original X-ray beam, film A in Fig. 1. (The film B is used

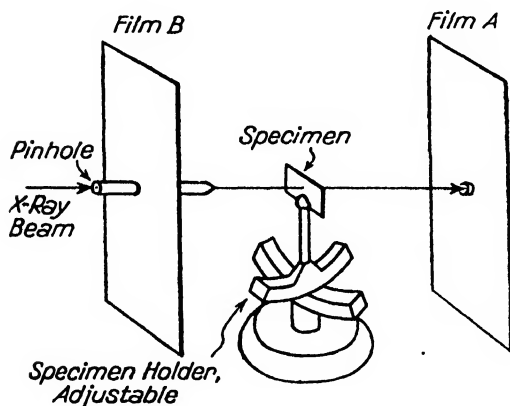


Fig. 1. Laue camera. Film A records the transmission pattern, film B the back reflection pattern, usually not simultaneously.

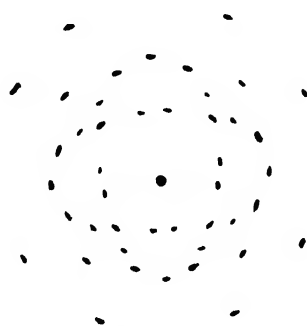


Fig. 2. Laue pattern (transmission type) with X-ray beam approximately parallel to a crystal axis of four fold symmetry. Undistorted crystal.

only for the back reflection method referred to below.) On the photographic plate the diffracted rays make a pattern of spots, as in Fig. 2, each spot being the reflection of a certain wave length from a certain crystal plane in one or more orders. The X-ray tube is best equipped with a target of tungsten and operated at 50,000-60,000 volts. The radiation emitted under these conditions contains a broad band of wave lengths (general or "white" radiation).

The diffraction spots are arranged on ellipses which have one end of their major axes at the central undiffracted spot. All the spots on any one ellipse are due to reflections from planes of a single zone (planes parallel to a common line known as the zone axis). As the spots are formed by rays of different wave lengths, their blackness depends not only on the arrangement of atoms in the crystal, but also on the intensity of the wave lengths in the X-ray beam, and on the sensitivity of the photographic emulsion to the different wave lengths.

The Laue method is useful for the determination of crystal structure. Indices may be assigned to the spots by various methods, the most convenient being the gnomonic projection. The symmetry properties of a crystal may be determined from the symmetry of the Laue patterns; when an X-ray beam passes through the crystal parallel to a four fold rotation axis, for example, the pattern will coincide with itself if given one quarter turn about the center (Fig. 2). The symmetry elements deduced from Laue patterns will always include a center of symmetry, whether or not the crystal possesses one. Large quantities of data on the

relative intensity of reflection of different planes can be obtained from Laue patterns when proper precautions are taken, and are of value in determining atomic positions in the unit cell.

The Laue method reveals imperfections resulting from accidents of crystal growth or from deformation.^{3,5} The Laue spots from perfect crystals are sharp, as in Fig. 2; whereas imperfect crystals or plastically deformed crystals produce blurred images and spots elongated radially as in Fig. 3 giving the appearance known as "asterism." An analysis of this can give the range of orientation of the reflection planes,^{3,6} and can indicate the severity of the deformation received by the specimen, but does not provide a reliable means of quantitatively measuring stresses.⁴ The Laue method is also useful for determining the orientation of single crystals.^{1,2} For this purpose the symmetry of the pattern may be noted or it may be plotted on a stereographic or gnomonic projection.

Back Reflection Laue Method—The most convenient arrangement for orientation work is the back reflection Laue camera, in which the film is mounted over the pinhole system, at B in Fig. 1, the film registering the rays that are diffracted back toward the X-ray tube. The analysis of back reflection Laue patterns for single crystal orientation is done by stereographic projection,⁷ and is too detailed for presentation here. Crystals must be reasonably perfect for this method, as the spots overlap and become indistinguishable if imperfections amount to more than two or three degrees.

The "Pinhole" Method⁸—The "pinhole" method is a combined Laue and powder method that is so often used in practical work as to deserve separate discussion. Because most practical applications of the pinhole method are simple and easily understood, they are presented before the powder method and will serve somewhat as an introduction to the latter. The apparatus is identical with that of the Laue method, except that radiation is not purely general (white), but also contains strong monochromatic components. Molybdenum target tubes are used, operating at a voltage of 30,000-45,000 volts and giving strong monochromatic (characteristic) lines at a wave length of 0.71 Angströms (actually a close doublet of this average wave length) and a weaker line at 0.63 Angströms, the $K\alpha$ and $K\beta$ lines, respectively. The specimens are polycrystalline materials—in the case of steel either wires or thin strips about 0.004-0.010 in. thick. Patterns from coarse grained materials contain many spots, as in Fig. 4. Throughout a series of exposures in a given camera, the size of the spots is proportional to the size of the grains and the number of spots is proportional to the number of grains per unit of volume of the specimen, provided the grains are smaller than the effective cross section of the X-ray beam. As the number of spots increases, circular diffraction rings appear (see following section). At first the rings are granular, but as the number of spots increases (that is, the grain size decreases) the rings become continuous and smooth. Just as in the Laue method, a lengthening of the spots, "asterism," is caused by crystal imperfection or plastic deformation.



Fig. 4. Pinhole pattern of undistorted polycrystalline material. Typical of recrystallized metal.

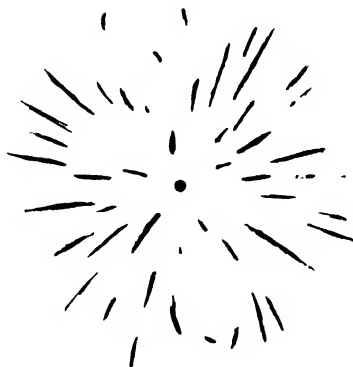


Fig. 3. Laue pattern of a distorted crystal, showing asterism.

The distribution of intensity around the diffraction rings reveals the presence or absence of a preferred orientation of the grains (fiber textures). Random orientations produce rings that are uniformly black all around; highly developed orientations give the appearance of Fig. 5, which is a tracing of a pattern from rolled steel. In the cold rolling of steel, preferred orientation begins to be detected at reductions of 20-40% in thickness and gradually increases in perfection until the pattern resembles Fig. 5 at 90-95% reduction.

Upon recrystallization, the rings break up into spots again and may or may not show the same intensity maxima. The preferred orientations after recrystallization have been analyzed in this way and some are found to be the same as in the

cold worked material, some new ones are found, and frequently the recrystallization produces a random orientation.⁹ The presence or absence of preferred orientations can only be determined if there are many spots in the pattern (more than in Fig. 4, for example) and in coarse grained material it is often necessary to shift the specimen during the exposure to provide a sufficient number of spots.

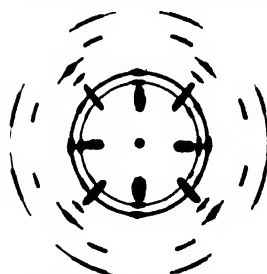


Fig. 5. Pinhole pattern (transmission) of sheet steel having a preferred orientation from cold rolling. (Rolling direction vertical, sheet surface perpendicular to the X-ray beam.)

A series of pinhole patterns taken with different angular settings of the specimen with respect to the beam is necessary to study all orientations of the grains. It is customary to plot the data from a series of exposures of this type on a stereographic projection;^{9, 10, 11} this plot (which is actually a map of the relative frequency of different orientations of a crystal plane) is known as a pole figure. Industrial problems frequently do not require such an extended study, and a single picture with the beam perpendicular to the strip or wire specimen often supplies all the required information.^{4, 7} Internal stresses and the recovery from a stressed condition are not readily shown with pinhole pictures.

A convenient arrangement for determining the depth of cold work produced by machining is to have the beam strike the specimen at an oblique incidence and reflect from the surface of the specimen, rather than penetrate it.^{4, 7} If the surface is cold worked, the spots will be blurred and may overlap into continuous rings, but after etching to a depth sufficient to remove the cold worked layer the spots become sharp. Back reflection cameras, discussed in the following section, are also much used for this purpose.

Powder Method^{1, 9, 12}—Radiation—The powder method employs monochromatic radiation falling on a powdered crystal specimen or a fine grained polycrystalline specimen. Radiation is obtained from X-ray targets of relatively low atomic number giving weak general radiation and relatively strong characteristic radiation. Molybdenum targets may be used but are not satisfactory unless a zirconium filter is placed over the photographic film in the camera. Best results are obtained by choosing targets of Fe, Co, Ni, Cr, or Cu, or alloys of these. The target is chosen so that the characteristic $K\alpha$ radiation is of longer wave length than the K absorption limit of the specimen in order to avoid fogging of the film by fluorescent radiation originating in the specimen.

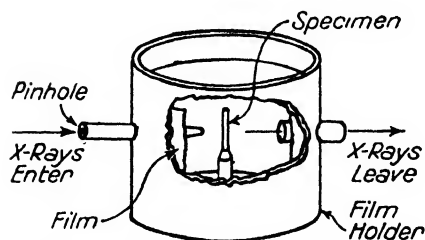


Fig. 6. Powder camera (Debye-Scherrer-Hull)

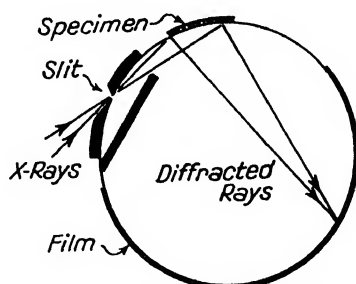


Fig. 7. Focusing camera (Seeman-Bohlin, Phragmen).

Cameras—Powder cameras are of various types. The common Debye-Scherrer-Hull type (Fig. 6) consists of a cylinder on which is mounted the photographic film, a rod shaped specimen on the axis of the cylinder, suitable slits or pinholes to direct the primary beam at the specimen, and a device to catch this undiffracted beam or conduct it out of the camera after it has penetrated the specimen, thus avoiding intense blackening where it strikes the film. Focusing cameras are also cylindrical but are designed so that the specimen, the slits, and the photographic film all lie on the circumference of the cylinder (Fig. 7). This arrangement causes diffracted rays from all parts of the specimen to come to a focus on the film and give sharp lines with relatively shorter exposure time.^{9, 12} Back reflection cameras employ large angle diffracted rays only. They may be constructed with a cylindrical

film, with a flat film, or with a photographic plate (see B, Fig. 1); a hole is provided in the film or plate for the passage of the primary X-ray beam. Any of these types may be modified to operate with the specimen at either high or low temperatures, and for use with large grained samples they may be provided with devices to oscillate or shift the specimen in order to give more grains a chance to reflect the X-rays.

For studies of cold work and annealing, simple back reflection cameras serve well.¹ Co and Fe radiation are used for steel and copper specimens, and Cu radiation for aluminum specimens, to give a strong diffraction line at a large angle. The pinholes need not be as small as in cameras used for precision lattice constant determinations. Cold work is shown by a blurring of the spots lying on the diffraction rings and a broadening of the rings, as indicated in Fig 8 and 10. Recovery

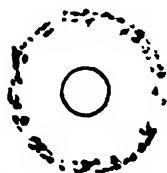


Fig. 8. Pattern from distorted polycrystalline material in a back reflection camera (Film B, Fig. 1). Blurred spots form a ring surrounding the central hole in the film.

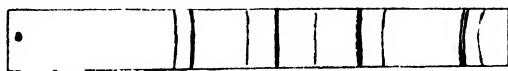


Fig. 9



Fig. 10

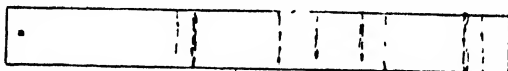


Fig. 11

Fig. 9. Powder pattern of annealed iron, from camera of Fig. 6, with FeK α and FeK β radiation. Increasing θ from left to right.

Fig. 10. Pattern from cold worked iron. Lines widened and weakened by "microscopic" internal stresses.

Fig. 11. Pattern from recrystallized iron, the large unstrained grains forming spotty lines.

from the strained condition is indicated by a sharpening of the lines (compare Fig. 9, annealed, with Fig. 10), and may or may not go on simultaneously with recrystallization, which is indicated by a return of the spotty type of pattern as in Fig. 11, indicative of large strain-free grains. This type of camera is not as useful for determining preferred orientations as the "pinhole" camera that produces its pattern in the forward direction.

The Diffraction Pattern—When a primary beam of X-rays strikes a specimen the diffracted beams leave the specimen along the generators of a number of cones, each of the cones being concentric with the primary beam. These cones fall on a flat film forming concentric circles, or on a cylindrical film forming curved lines, as indicated in Fig. 9. These are frequently called "Debye rings." From the diameter of the circles or arcs on the pattern and the known dimensions of the camera, the apex angles of the cones are calculated, and from these are obtained the angles of reflection, θ , of the Bragg equation. In the camera sketched in Fig. 1, with the film at A, if x is the radius of a diffraction ring, and X is the perpendicular distance from the specimen to film, then $\tan 2\theta = x/X$. In the camera of Fig. 1, with the film at B, $\tan (180 - 2\theta) = x/X$. In the camera of Fig. 6, if s is the circumferential distance from the central undiffracted spot to an arc of the diffracted line, and R is the camera radius, θ is given in radians by the relation $\theta = s/2R$ (1 radian = 57.30°); in practice, measurement is best made of the distance $2s$, from arc to arc, rather than s , from arc to central spot. In the camera of Fig. 7 (and frequently in the others also) it is convenient to prepare a calibration chart for reading θ or d directly from the positions of diffracted lines. A sample whose lines fall at accurately known angles provides the data for such a chart.

Thus, from the position of the lines on the film the spacing d of the corresponding atomic planes may be obtained. The sequence of lines on the film corresponds to the sequence of interplanar spacings in the crystal. The pattern in Fig. 9, for example, shows a sequence characteristic of body-centered cubic crystals. Large unit cells have all their interplanar spacings large, and thus their diffracted lines will lie at small angles from the direct beam, while small unit cells will have lines spread out at larger angles. It is the size and shape of the unit cell of a crystal

that governs the *positions* of the diffracted rays, while the atomic arrangement within the unit cell controls the *intensities* of the rays. The determination of crystal structure from the powder diffraction patterns is a complex procedure that yields a reliable result in only the simplest cases. Numerous summaries are available of the principles involved and of the various tables, graphs, and other devices to aid the investigator.^{1, 9, 11, 13}

Strictly monochromatic radiation is not usually available, for the targets of X-ray tubes emit radiation of a series of wave lengths, each of which forms a diffraction pattern on the film independently. The $K\alpha$ lines with closely similar wave lengths fall together and make a single line at low values of θ , but form a doublet at large values of θ (provided the specimen is able to yield sufficiently sharp lines). The $K\beta$ radiation, if not filtered out, produces another superimposed spectrum, which is of single lines instead of doublets and is always weaker than the $K\alpha$ spectrum. Its lines are recognized by these characteristics and by the fact that the ratio of $\sin \theta$ for $K\alpha$ and $K\beta$ radiations reflecting from a given atomic plane always equals the ratio of the corresponding wave lengths. The $K\beta$ radiation may be removed by filtering, if desired; zirconium filters are used for molybdenum radiation, and nickel filters for copper radiation. The filters are best placed between the specimen and the film.

Amorphous materials, glasses, liquids, and gases give only broad halos instead of sharp lines. Analysis of such patterns has nevertheless given a large amount of information of scientific and practical value.^{14, 15} Better patterns are obtained when a crystal monochromator is inserted in front of the powder camera to provide strictly monochromatic radiation, but exposure times are thereby increased several fold.

Precision Lattice Constants—The accuracy of lattice dimension measurement with the Debye-Scherrer-Hull cameras and focusing cameras is from 0.1-0.02%, depending on the care taken and the operator's skill. Back reflection cameras are more precise, for these will give from 0.02-0.003%. Sources of error which enter in determining lattice constants with Debye-Scherrer-Hull cameras include: Incorrect centering of the specimen on the axis of the camera, finite size of the specimen and absorption of the rays in the specimen, shrinkage or expansion of the film on development and afterwards, incorrect determination of the camera radius, lack of parallelism in the primary beam, and deviations from Bragg's law caused by index of refraction of X-rays. Corrections for these errors and for the errors in back reflection cameras have been carefully studied by numerous investigators.^{11, 16, 17, 18, 19}

Identification of Phases—A great number of practical problems require no crystal structure determination, but merely an identification of phases by their powder diffraction patterns, and this may be done without involved calculations by simply comparing patterns of the unknown material with patterns of chemically or mineralogically identified material.⁷ The films are laid side by side or superimposed, and the similarities are observed directly. For this work large range cameras are required, so that many lines will be obtained. If a large number of patterns from known materials are to be compared with the unknown, the comparison can best be made by first noting the position on the film of the strongest lines of each pattern.²⁰ For identification to be certain, every line of the pattern must be accounted for. Important advantages of this X-ray method of identification are that only small quantities of material are required (a few mg.), and that different compounds or states of combination of the same elements are distinguishable from each other, since they possess different crystal structures. Thus, chemical compounds are distinguishable from mixtures. The method is widely used for the identification of alloy phases; it is more direct and positive than metallographic methods, but generally is inapplicable when a phase constitutes less than 1-5% of the weight of the alloy.

If more than one variety of crystal is present in any specimen, each will produce its spectrum independently, and the pattern will consist of superimposed spectra with relative intensities dependent on the relative amounts of the two phases. If a series of alloys is prepared of various compositions spaced across a binary constitutional diagram, the powder patterns will follow the alternate single and two phase regions of the diagram.¹² Superimposed spectra from three or more phases may occur with alloys of more than two constituents, or in some alloys in which equilibrium has not been obtained.

Solid Solutions—The presence of solute contracts or expands the dimensions of the unit cell of the pure solvent material. This is registered on the powder photo-

grams by a displacement of the lines to either greater or smaller diffraction angles, unless the effect is too small to be recorded. The effect is ordinarily proportional to the atomic per cent of the dissolved element (Vegard's law) or closely approximates this. The expansion or contraction comes to an abrupt halt at the solid solubility limit, and throughout the two phase region beyond the limit the lattice dimensions remain constant in binary alloys. This behavior enables an accurate determination of the solubility limit (and its variation with temperature) and is preferable to determining the limit from the appearance of the lines of a second phase in the patterns.⁷ The method is applicable to determining the range of homogeneity of intermediate phases as well as solid solutions of elements, and is applicable (in altered form) to ternary alloys²⁸ as well as to binary alloys.

The following precautions must be taken in determining solid solubility:^{7, 28} A thorough homogenization treatment is necessary, for the specimen must be free from concentration variations; the surface must be free from sublimation, oxidation, or other reactions which would alter the surface concentration; if the specimen is to represent the condition of the alloy at the homogenization temperature, the quenching from this temperature must be sufficiently rapid to prevent changes, and yet quenching stresses must not be introduced into the specimen. These stresses can best be avoided by quenching small wires or finely powdered material. The precision of this X-ray method of determining solid solubility varies with different alloys, in many cases exceeding that of other methods.

The interstitial or substitutional nature of the solid solution can be determined from powder diffraction patterns. The patterns give the dimensions of the unit cell, and from these data, together with the number of atoms per unit cell, the atomic weight of each atom, and the composition of the alloy, the theoretical or "X-ray" density is computed—assuming either interstitial or substitutional dispersion of the solute; comparison of these calculations with the actual density will establish the nature of the solution.^{8, 11} X-ray and measured densities always agree within the limit of error of the measurements when the proper crystal structure has been assigned.

Solid solutions are ordinarily random arrangements of the different kind of atoms on the lattice points. When one kind of atom migrates to a particular set of atomic positions in preference to others, a superlattice is formed.^{8, 21} This is recognized in the diffraction pattern by the additional "superlattice lines" which appear after a suitable low temperature annealing treatment in certain alloys.

Stress Measurement—Internal and applied stresses in metals may be studied with powder diffraction cameras. When an interplanar distance d is altered by stresses the diffraction angle changes accordingly. If the elastic strain varies from grain to grain in a polycrystalline metal the angle of diffraction will also vary, giving a widened diffraction line in the powder photograph as in Fig. 10. The amount of widening beyond the normal width of an annealed stress free material indicates the amount of variation of stress from point to point in the metal, the relative intensity of "microscopic" stresses. Other factors than stress, however, may contribute to the widening and must be considered in interpreting the photograph;⁴ namely, inhomogeneity in composition of the specimen and small size of the reflecting grains. If stresses are of equal intensity in all the reflecting grains, forming a homogeneous stress system, the diffracted rays from all grains will superimpose to produce sharp lines displaced from their normal unstressed positions. The diffraction pattern can then be used to calculate the homogeneous "macroscopic" stresses.^{4, 7, 9} Back reflection powder cameras, arranged so that the X-ray beam falls perpendicularly upon the specimen surface, give data from which the sum of the two principal stresses lying parallel to the surface is calculated; cameras providing oblique incidence of the rays are used to calculate the principal stresses individually. An accuracy in stress measurement by these methods of 1,500-3,000 psi. has lately been attained with laboratory conditions and with favorable materials, but depends greatly upon the skill with which the operator attends to such matters as constancy of temperature of specimen and film, film shrinkage or expansion, provision that in both the stressed and unstressed conditions the specimen has the same solid composition, and preparation of the specimen so that the surface is free from a cold worked layer and is fine grained. The nature of the method is such that only stresses in the outer fibers of the specimen are observed, and it is not applicable to cold worked metals.

Rotating Crystal Method: Photogoniometers—Types of cameras seldom used in practical work, but indispensable in crystal structure determination, are those in

which a single crystal is mounted so as to oscillate or rotate around a definite crystallographic axis.^{1, 11} Monochromatic radiation is used, and the simpler cameras are similar to Fig. 6. Modifications of this are particularly helpful for solving complex crystals. The most common of these is the Weissenberg photogoniometer, which permits a photographic film to be shifted in synchronism with the oscillation of the crystal and is provided with a slit through which only selected rays from the crystal will pass. Spacings of the layers of spots in rotating crystal patterns give the distance between lattice points in the direction of the axis of rotation of the crystal. The assignment of indices to each of the spots is easily accomplished by graphical means derived from the reciprocal lattice projection.^{1, 11, 12} The orientation of single crystals may be determined with these types of cameras and also conveniently by the modification devised by Davey and outlined in detail by Wilson.¹³

Spectrometers—The most accurate method of measuring the intensity of diffracted rays involves the use of an ionization chamber mounted on a spectrometer somewhat similar to an optical spectrometer.^{1, 14} The current in the chamber, measured by an electrical device, is proportional to the intensity of the X-ray beam. The method is used in crystal structure determination, particularly with the newer technique^{1, 14} that involves Fourier analysis of X-ray intensities to yield almost directly the distribution of electrons and atoms in the crystal, but is seldom required in practical applications.

Chemical analysis is accomplished by X-rays through the use of spectrometers that photograph the characteristic X-ray emission lines or absorption edges of the sample to be analyzed.^{1, 15} Favorable combinations of elements permit extreme sensitivity in the detection of small percentages of an element in a compound or mixture (independent of its state of chemical combination), and, with care, fair precision in quantitative analysis is possible.

Summary of Applications and Methods Usually Employed

Preferred Orientations of Grains, Fiber Textures—Pinhole method, with beam transmitted through the specimen or reflected from the surface of the specimen, noting intensity maxima around Debye rings (Fig. 5).

Cold Work and Recrystallization—Pinhole method with transmission or back reflection cameras (Fig. 4, 8).

Identification of Phases—Powder method with cameras having a wide range of reflection angles (Fig. 9).

Precision Lattice Dimensions; Boundaries of Regions in Phase Diagrams; Studies of Solid Solution and Aging—Powder methods with precision back reflection cameras.

Grain Size—If larger than 10^{-3} cm., pinhole method or powder method, noting size of spots (Fig. 4, 11). If smaller than 10^{-3} cm., powder method, noting widths of lines (Fig. 10).

Perfection of Lattice in Grains—Pinhole, Laue, or back reflection powder methods, noting sharpness of spots.

Homogeneous (macroscopic) Internal Stresses or Applied Stresses—Precision back reflection powder method, with measurement of lattice dimensions.

Heterogeneous (microscopic) Internal Stresses and Recovery—Back reflection powder method, noting width of lines.

Orientation of Individual Grains—Laue, back reflection Laue, or rotating crystal methods, or photogoniometer.

Determination of Crystal Structure—Powder method only in very simplest cases; rotating crystal or photogoniometer method frequently supplemented by Laue patterns.

Structure of Amorphous Solids, Glasses, Liquids, and Gases—Powder method or spectrometer.

Chemical Analysis—Photographic spectrometer, registering emission lines or absorption edges.

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Heat Treatment of Metals*

By R. S. Archer*

Introduction—The purpose of this article is to present certain fundamental principles which are applicable to the heat treatment of all metals—ferrous or nonferrous. Another article will deal more with the heat treatment of iron and steel, giving facts and figures relating particularly to the treatment of those materials. These articles, general in nature, are intended to serve as a foundation for specific articles describing the heat treatment of certain parts, such as gears and dies, and of certain nonferrous alloys. It is hoped that the need of repeating fundamental principles in the subsequent specific data sheets may be avoided by referring to these general data sheets.

Heat treatment is defined as an operation or combination of operations involving the heating and cooling of a metal or an alloy in a solid state for the purpose of obtaining certain desirable conditions or properties.¹

It is usually desired to preserve as nearly as possible the form, dimensions, and surface of the article being treated.

General Principles—The desirable changes in conditions or properties may be considered as due to changes in structure. Changes in internal stresses are frequently objects of heat treatment. Usually it is desired to decrease or relieve such stresses, although occasionally it is desired to set up stresses of a definite kind. Changes in internal stress are associated with changes in interatomic spacing. Hence, even stress changes can be considered as due to changes in structure if we regard interatomic spacing as one of the elements of structure.

More frequently, the changes effected by heat treatment involve changes in the nature, form, size, or distribution of the structural constituents. Changes in the nature of the constituents result from the effect of temperature on phase equilibria or from changes in the composition of material, as in the case of carburizing or nitriding. The form of constituents is affected by the conditions under which they separate from solid solutions, and by the tendency to assume equiaxed shape at temperatures which permit diffusion and atomic rearrangement (spheroidizing). Changes in the arrangement or distribution of constituents in a solid metal can be brought about by solution and reprecipitation, as when the granular cementite of an annealed tool steel is converted to the lamellar cementite of pearlite by normalizing.

Factors in Heat Treatment—Heat treatment consists of subjecting a metal to a definite time-temperature cycle. The chemical effect of the medium surrounding the metal may be of importance, as in carburizing and in nitriding. The time-temperature cycle may conveniently be divided into three parts: (1) Heating, (2) holding, (3) cooling.

Heating—The rate of heating determines the changes within the metal during this phase of the heat treatment, and the heating medium is important insofar as it affects this rate, and causes or prevents chemical changes, such as oxidation, proceeding from the surface of the metal. It is necessary to consider not merely the average rate of heating, but the rate of heating desirable or permissible at each stage of rise in temperature. In any case, the rate of heating is seldom constant and usually decreases as the final or holding temperature is approached, so that this temperature can be attained more accurately and uniformly.

The heat actually consumed in the practical heating of a metal to a given temperature is equal to the heat content of the metal at that temperature,² less the heat content of the metal at the beginning of the heat treatment operation, and plus the heat losses due to radiation during the heating process. These heat losses increase, other things being equal, with the duration of the heating operation.

From the standpoint of its effect on the metal, rate of heating may be important

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¹See definition of "Heat Treatment" in this Handbook.

²See "Heat Content of Metals" in this Handbook.

insofar as it affects internal stresses, distortion, grain growth, or chemical changes such as oxidation.

If a piece of metal initially free from internal stresses is heated uniformly, no internal stresses will be set up. If the heating is not uniform, so that different parts of the piece acquire different temperatures at a given time, internal stresses will be set up which will cause distortion and in brittle metals may cause rupture. Uniform heating is favored by uniform application of heat, slow application of heat, and high heat conductivity of the metal itself. Particular care is required in the heating of brittle metals having poor heat conductivity, for example, hardened high speed steel.

The extent of normal grain growth is determined chiefly by maximum temperature and the time at or near the maximum temperature. Abnormal grain growth or germination, however, may be affected by rate of heating. A tendency toward germination is apt to be present in metals which have been work hardened slightly rather than severely, or in metals in which there are marked variations in the degrees of work hardening from one point to another. When such conditions exist, it is frequently possible to prevent or minimize abnormal grain growth by heating the metal very rapidly above the germinative temperature, which usually means heating rapidly to well above the temperature of recrystallization.³

Surface changes resulting from contact with the heating medium are naturally less during the heating cycle, other things being equal, the shorter the duration of this cycle. Rapid heating obtained by the use of a strongly oxidizing and active flame, on the other hand, might result in more oxidation than a slower heating with a more neutral flame.

Holding at Heat—Usually a certain time period, more or less definite, is required at the maximum temperature of the heat treatment. First, the time must be sufficient to permit the entire article to come to a uniform temperature, except in the comparatively rare cases where a nonuniform distribution of temperature is desired, as in the localized hardening of steel. Time to attain uniform temperature increases with the thickness of the heaviest section of the piece and is greater the lower the thermal conductivity of the material. The rate of heating employed must also be considered, since with slow heating a fair degree of uniformity may exist shortly after the metal has come to temperature.

The next requirement is that the time at heat be sufficient to allow the desired changes to take place within the metal. Most of these changes involve diffusion, and, in the case of wrought metals, grain growth. The solution of constituents such as carbides in steel depends upon diffusion away from the particles of such constituents. The conversion of combined to graphitic carbon in the annealing of malleable castings involves the diffusion of carbon from the carbide particles to the graphite nuclei. Case carburizing involves the diffusion of carbon from the surface toward the center.

Grain growth does not occur to any appreciable extent on reheating cast metals which have not been subjected to plastic deformation after casting, except in the case of iron and its alloys, which undergo recrystallization on heating through Ac-3'. Metals which have been plastically deformed, either hot or cold, exhibit grain growth at temperatures above what is known as the temperature of recrystallization. It is this grain growth which is responsible for the softening of work hardened metals on annealing. Grain growth is therefore not only desirable but necessary in the annealing of cold worked metals for the purpose of softening. Occasionally a very large grain size is desired, as in the treatment of certain metals for strength at high temperatures. In general, however, it is desired to limit the development of large grains since excessive grain size leads to various undesirable properties. Since both diffusion and grain growth require atomic mobility, these processes usually occur within approximately the same range of temperature. In the heat treatment of steel, it is commonly desired to bring about certain structural changes which depend upon diffusion, and to avoid as far as possible the grain growth which is apt to occur in the same range of temperature.

It is thus evident that the laws of grain growth and diffusion play an important part in the determination of temperature and time at heat.

³Science of Metals, McGraw-Hill Book Co., p. 136.

⁴See the article "Iron-Carbon Diagram" in this Handbook.

Recrystallization temperatures for certain metals after severe cold plastic deformation are given in the following table:

Recrystallization Temperatures^a

Approximate Lowest Recrystallization Temp., °F.

Iron	840	Magnesium	300
Nickel	1110	Tantalum	1830
Gold	390	Tungsten	2190
Silver	390*	Molybdenum	1650
Copper	390	Zinc	Room temperature
Aluminum	300	Lead	Below room temperature
Platinum	840	Tin	Below room temperature
		Cadmium	About room temperature

*Indications are that under certain conditions silver will recrystallize at lower temperatures.

These temperatures are higher the less the degree of cold working. Time is also a factor, and recrystallization can be brought about at temperatures which are lower the longer the time allowed at temperature. Impurities raise the temperature of recrystallization. For example, brass requires a slightly higher temperature than copper.

Grain size normally increases with both temperature and time of exposure. At a given temperature an apparent equilibrium grain size is eventually reached which does not change greatly on further increase of time. The time required to attain this condition may be a few seconds at temperatures just under the melting point, and a matter of days just above the recrystallization temperature. In practical heat treating the temperature is usually high enough to permit fairly rapid approach to grain size equilibrium, so that temperature rather than time is the more important factor governing grain size. In general, however, time is sufficiently important so that the duration of a heat treatment is not prolonged unnecessarily beyond the time required to produce whatever other changes in structure are desired.

The rate of diffusion increases rapidly with temperature. It also depends greatly on the nature of the dissolved substance. In most cases it seems that the dissolved substance diffuses in atomic form, and rapid diffusion is perhaps opposed by large atomic volume. Carbon diffuses rapidly in iron at temperatures above A₁, while phosphorus and certain other elements diffuse very slowly, even at much higher temperatures.

The time required to bring about a certain change involving diffusion depends not only on the rate of diffusion, but on the distances through which diffusion must take place. The time required is, therefore, longer the coarser the initial structure of the material.

Metals and alloys which are elastic at ordinary temperatures are left in a state of internal stress by all commercial cold working processes. High internal stresses can also be produced by uneven temperature changes. Rapid cooling, uneven sections, and mass contribute to such stresses. Severe stresses are set up in steel by the hardening operation, both by uneven temperature changes in themselves and by the volume changes incident to hardening and aging.

The reduction of internal stress by heat treatment is dependent on a slight plastic flow which is allowed to take place by the lowering of the elastic limit at the temperature at which it occurs. It is probable that any metal must be heated to a temperature near its recrystallization temperature to remove stresses; heating to higher temperatures will result in more complete removal. The extent to which stresses are removed is greater the higher the temperature and the longer the time of heating. It is well to keep in mind that even after internal stresses have been substantially removed by heating at a relatively high temperature, new stresses may be established during cooling.

Sometimes the object of heat treatment is best attained at temperatures just under the melting point of the most fusible portions of the material. This is apt to be the case where the effect desired depends on bringing into solution one or more constituents whose solubility increases progressively with temperature up to the point of incipient fusion, as in the hardening of high speed steel and duralumin. Occasionally materials of this class can be heated to such a temperature that some fusion takes place and then, either with or without subsequent treatment, they may have desirable properties. As a general rule, however, it is not safe to heat treat at temperatures which cause any fusion within the material.

^aScience of Metals, McGraw-Hill Book Co., p. 86.

When the object or one of the objects of heat treatment is to bring about certain phase changes in an alloy, there are rather definite temperature limits within which the desired change can take place. The permissible range of temperature is defined by the constitution diagram of the alloy. The selection of the most desirable temperature within the permissible range is influenced by the considerations mentioned above regarding grain growth, diffusion, and internal stresses, as well as by other practical considerations concerning distortion, scaling, and operating economy.

Above the recrystallization temperature metals deform plastically under low stresses. Objects undergoing heat treatment, therefore, may deform under their own weight or from any means of handling which imposes even fairly low stresses on the material. Low temperature and short time oppose the distortion of objects under their own weight, and low temperature minimizes distortion. Special means are often employed to hold articles in shape during heat treatment. Castings may have members cast into them solely for this purpose, such members being cut out after heat treatment. Fixtures may be employed in the heat treating furnace to prevent sagging at the high temperature. Closed, hollow articles may be supported by internal air pressure.

The cost of holding metals at a given constant temperature is made up of the heat losses of the furnace due to radiation and the like, the burden on the heat treating equipment, and, in the case of long heat treatments, the cost of holding the material itself in process. Heat treatments of long duration involve interest charges on the material itself, and also certain losses or difficulties resulting from interference with precise scheduling of manufacturing operations. It may be pointed out that the energy consumed or given off as a result of changes taking place within alloys during heat treatment is very slight in comparison with other factors of heat treatment cost.

Cooling—In the case of pure metals or single phase alloys in the form of articles of simple shape, which are usually heat treated primarily for the purpose of softening after cold working, rate of cooling is likely to be quite unimportant and therefore determined largely by convenience. The rate of cooling after the annealing of copper and alpha brass, for example, has little effect on the properties of the material, although the specific manner of cooling may have considerable effect on the surface of the material. It is necessary in each case, however, to consider whether a metal is really pure from the standpoint of heat treatment effects. Some commercially pure metals contain sufficient quantities of certain impurities to produce appreciable effects during cooling. It is becoming recognized, for example, that very small amounts of carbon, oxygen, nitrogen, and perhaps phosphorus may cause substantial changes in the properties of iron at temperatures below the critical range.

When the constitution of the material being heat treated is different at the maximum temperature of heat treatment from the constitution stable at low temperatures, rate of cooling is of great importance in determining the result of the heat treatment. Very slow cooling permits full development of the constitution stable at low temperatures. Rapid cooling may preserve in an unstable condition the structure which was produced at the high temperature, as in the quenching of austenitic steels and duralumin. Frequently, as in the case of plain carbon steels, the most rapid cooling possible will not preserve the high-temperature structure.*

Iron-carbon alloys cooled from above the critical range with sufficient slowness to permit the full development of low temperature structural equilibrium would consist either of ferrite and graphite or ferrite and spheroidized carbides. The intermediate structures obtained in the hardening, normalizing, and annealing of steel thus result from intermediate and controlled rates of cooling. Not only the average rate of cooling, but also the rate at each stage of the cooling operation is important.

Heat Application—Heat is imparted to metal objects by the usual processes of radiation and conduction. At high temperatures, radiation is a very important factor in the transfer of heat. In furnaces operating below approximately 1000°F., positive circulation of the furnace atmosphere is desirable to promote rapidity and

*It has been shown by Mathews that, in certain steels at least, the amount of austenite retained is greater after moderately rapid cooling, as in oil, than after a more rapid cooling, as in water. This is presumably because the internal stresses set up by water quenching help to initiate the change from gamma to alpha iron.

uniformity of heating. Heat may also be developed within the metal by the passage of electric current, led into the metal by means of contacts, or generated by induction. Means employed in heat treating include furnaces fired with oil, gas, coke, or coal; furnaces heated by electrical resistors of both metallic and nonmetallic types; liquid baths of lead, salt, or oil in which the objects to be heated are immersed; and containers into which steam is introduced.

Electrical Resistance Heating—The heating of metals by the direct passage of electric current through the work itself is quite limited in practical operation for obvious reasons. If a uniform temperature is desired, the metal object must be of uniform cross section. Steel tubing has been heated for hardening by applying contacts at the ends of each tube and passing current through the tube until the desired temperature is reached. The passing of the tube through the Ac₁ point is indicated by the discontinuity in thermal expansion. Resistance heating has been used in heating bar stock for forging, in heating rivets, and in the sintering of tungsten briquettes. In certain cases where a nonuniform distribution of temperature is desired, resistance heating may be applied to an article of nonuniform cross section (for example, in the heating of ends of valve stems for hardening).

Temperature Gradients in Heating—In resistance heating, the inside of the metal is normally hotter than the outside surface. Hence, the estimation of temperature by the color of the piece, by radiation or optical pyrometers, or by thermocouples placed outside the piece is apt to give low results.

In other methods the heat is introduced into the metal through the surface, and as long as the temperature is rising, the surface is hotter than the interior. Allowance must again be made for this difference, and in practice it is recognized that a certain period of time, increasing with the weight of the section, is required for the penetration of heat throughout the entire cross section of the piece. Heavy sections therefore lag in coming up to temperature.

Limitations on Rate of Heating—With resistance heating the rate of heating is limited only by the current available. With externally applied heat the rate of heating is limited by the thermal conductivity of the metal. If it is assumed that the surface of the object to be heated is maintained at the maximum permissible temperature, as, for example, by immersion of a small object in a large bath of lead, the time required to saturate the object is determined by the heat capacity at the desired temperature and by the heat conductivity of the metal under the temperature gradients existing.

Fuel Fired Furnaces—Any temperature employed in the heat treatment of the common metals can be readily attained in fuel fired furnaces of either the direct fired or muffle type. Furnace parts, including muffles, made of heat resisting alloys can be used up to about 1800-2000°F., but may be attacked by fuels of high sulphur content. Refractories are satisfactory up to considerably higher temperatures for hearth, walls and muffles. Conveying mechanism, and rails, which must be made of metals, are at present limited to furnaces operating under about 2000°F., unless these parts are artificially cooled or are so placed and operated that they do not attain the full temperature.

Electric Furnaces—Electric furnaces heated by metallic resistors of the nickel-chromium or nickel-iron-chromium types are limited in working temperature to about 1800-2200°F., depending on the type of work and the permissible cost of resistor replacement. Platinum-wound furnaces may be used up to about 2700-2900°F., and resistors of molybdenum or tungsten operated in hydrogen provide furnace temperatures up to at least 3100°F., limited by the refractory rather than the resistor. Carbon (or graphite), in solid or granular form, can be used as resistor material up to very high temperatures, but is attacked by both oxygen and hydrogen. Industrial electric furnaces operating above the temperature range for nickel-chromium alloy resistors are at present usually heated by synthetic resistor bars consisting largely of silicon carbide, or by recently developed alloy resistors of the iron-chromium-aluminum type.

Furnace Atmospheres—One of the problems in the heat treatment of steel and some other metals is concerned with oxidation or the formation of scale,^{6, 7} and much is said regarding so-called "neutral" atmospheres. It is to be noted that there are

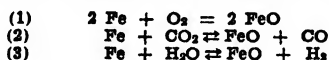
⁶C. Upthegrove and D. W. Murphy, Scaling of Steel at Heat Treating Temperatures, Trans., A.S.S.T., 1933, v. 21, p. 73.

⁷W. E. Jominy and D. W. Murphy, Scaling of Steel at Forging Temperatures, Trans., A.S.S.T., 1930, v. 18, p. 19-57.

no truly neutral atmospheres except the rare gases. These have actually been employed in special cases, but are too expensive for ordinary work. Other furnace atmospheres are to be regarded as chemically active, the kind and extent of the action depending on the composition of the metal, the composition of the atmosphere, and the temperature.

The most common atmospheres are those resulting from the partial or complete combustion of coal, oil, or gas. The possible ingredients of such atmospheres include oxygen, nitrogen, carbon dioxide, water vapor, carbon monoxide, hydrogen, hydrocarbons, sulphur dioxide, and (rarely) hydrogen sulphide. Of these, oxygen, carbon dioxide, water vapor, and sulphur dioxide are oxidizing. Hydrogen is reducing. Carbon monoxide may be reducing or oxidizing, but toward iron its effect is predominantly reducing. Nitrogen is substantially neutral toward most of the common metals at heat treating temperatures, but reacts with magnesium above about 750°F. to form a nitride. Sulphur dioxide and hydrogen sulphide may impart sulphur to steel.^{8,9} Hydrocarbons and carbon monoxide may carburize, while the oxidizing gases, and also hydrogen, may decarburize.¹⁰

The most common kind of action with which we have to deal is oxidation. All of the common metals are oxidized readily at heat treating temperatures. The heat resisting alloys depend for their protection on the formation of a thin scale of a kind that prevents or retards further oxidation.¹¹ The elements commonly used to produce these protective films are aluminum, chromium, and silicon. It is interesting to note that all three have in themselves a very strong affinity for oxygen.



Reactions (2) and (3) are reversible. A mixture of CO and CO₂ will oxidize iron at elevated temperatures if relatively rich in CO₂, but will reduce iron oxide if relatively rich in CO. Likewise, a mixture of H₂ and water vapor is oxidizing if high in water vapor, but reducing if high in hydrogen.

The compositions of gas mixtures which are neutral, with respect to oxidation and reduction, vary with temperature.^{12,13} For example, a mixture containing 65% hydrogen and 35% water vapor will reduce iron oxide at 1600°F., but will scale iron at 1000°F. A piece of iron could thus be heated in such an atmosphere indefinitely at 1600°F. without scaling, but would form a thin scale on cooling to room temperature in the same atmosphere. This atmosphere will not prevent the formation of scale on high chromium steels even at a high temperature, because slight traces of water vapor will oxidize chromium. The scale will no longer, however, have the normal brown appearance (due to iron oxide) but a dark green color characteristic of chromic oxide.¹⁴

The gases discussed above (resulting from combustion) also include most of those which are sometimes injected into furnaces or heat treating containers to produce a definite desired atmosphere. Ammonia is of special interest as a fairly cheap source, by decomposition, of a mixture of hydrogen and nitrogen.

Because a high percentage of commercial heat treating operations are applied to steel, the attainment of a furnace atmosphere which is nonoxidizing toward steel is of special interest. The complete combustion of the fuel produces carbon dioxide or water vapor or mixtures of these gases. Both of these gases are oxidizing toward iron. A nonoxidizing atmosphere resulting directly from the combustion of a fuel must therefore represent incomplete combustion, so that enough reducing gases such

⁸D. W. Murphy, Behavior of Steel in Sulphur-Containing Atmospheres at Forging Temperatures, Trans., A.S.T., 1933, v. 21, p. 510.

⁹D. W. Murphy and W. E. Jominy, The Influence of Atmosphere and Temperature on the Behavior of Steel in Forging Furnaces, Univ. Mich., Eng. Res. Bull. No. 21, Oct., 1931.

¹⁰W. E. Jominy, Surface Decarburization of Steel at Heat Treating Temperatures, Univ. Mich., Eng. Res. Bull. No. 18, March, 1931.

¹¹N. B. Pilling and R. E. Bedworth, Mechanism of Metallic Oxidation at High Temperatures, Trans., A.I.M.E., 1923, v. 68, p. 618.

¹²D. W. Murphy, W. P. Wood, and W. E. Jominy, Scaling of Steel at Elevated Temperatures by Reaction with Gases and the Properties of the Resulting Oxides, Trans., A.S.T., 1932, v. 19, p. 193.

¹³Iron Oxide Reduction Equilibria, U. S. Dept. of Commerce, Bureau of Mines Bull. No. 296, 1929.

¹⁴F. C. Kelley, Bright Annealing of Steels in Hydrogen, Trans., A.I.M.E., Iron and Steel Div., 1931, v. 95, p. 378.

as carbon monoxide and hydrogen are present to prevent oxidation. The fact that combustion must be incomplete imposes a limit on the flame temperature, depending on the heating value of the fuel and the temperature of the air (or oxygen) used for combustion. When a muffle or other device is used to separate the work from the products of combustion, the fuel may be completely burned outside of the container and any desired atmosphere may be maintained inside, using a separate source of gas if necessary. Commonly, an attempt is made to partly burn the fuel inside of the muffle and to complete the combustion outside of the muffle.

A considerable amount of heat treatment is being done in retorts, of both batch and continuous types, where the products of combustion do not come into contact with the work and where the atmosphere in the retort is controlled to produce definite results. In this way steel may be nitrided and carburized, and high carbon steels may be hardened without oxidation, stain, carburizing, or decarburizing.

The nature of the scale formed on steel may be of as great importance as its thickness, since a thick scale can often be removed more easily than a light scale. For example, nickel steels and stainless steels form a lighter scale under the same conditions than straight carbon steel but are apt to be more difficult to clean.

Steam Tanks—Steam may be used conveniently for the attainment of temperatures up to about 300°F. and is used especially in the precipitation heat treating of aluminum alloys.¹³ The condensation of the steam in the cold parts of the charge automatically results in rapid and uniform heating and temperature can be closely controlled by the regulation of pressure.

Liquid Baths—Liquid baths¹⁴ are available for heat treatment up to about 2300°F., those commonly employed covering approximately the following ranges:

Water	Up to 212°F.
Oil	Up to 500°F.
Salt	300-2300°F.
Lead	650-1700°F.

The temperature range given for salt baths covers several types of salt, no one type being suitable for the entire range. Liquid baths exclude air and furnace atmospheres from the work and are therefore protective unless the bath material itself has some undesirable action on the metal. Liquid baths also have the advantage of providing rapid heating, and great uniformity of temperature can be attained when the bath itself is sufficiently circulated and the work is left in the bath for a sufficient time. On the other hand, the very rapidity of heating, especially in the case of the lead bath, is especially useful for localized heating when this effect is desired.

Temperature Measurement—Accurate temperature measurement is vital in heat treatment. Usually it is best to measure accurately the temperature of the work itself, and the importance of properly placing thermocouples for this purpose is discussed in the article on Pyrometry in this Handbook. Often in the heat treatment of many articles of the same material (form and size) the operation is regulated by measuring the temperature, not of the articles themselves, but of some point in the furnace whose temperature bears a reasonably fixed relation to that of the work, when the work is in the furnace for the same time or traveling through the furnace at the same rate. In continuous furnaces, especially, this may be the most convenient method of control. There are obvious uncertainties in this method, however, and wherever possible it is preferable to determine the temperature of the work itself.

Quenching—Heat can be removed from a solid object only by dissipation from its surface. The rate of cooling of a given object from a given temperature depends therefore on the surface temperature of the object during the cooling process. The shortest possible time of cooling is obtained when the surface is maintained substantially at the temperature of the cooling medium; the time then depends on the thermal conductivity of the material.

The decreased surface temperature necessary to promote rapid cooling may be obtained by removing the object from sources of radiant heat, so that it can radiate its own heat freely without receiving return radiation, and by bringing into contact

¹³See "Heat Treatment of Wrought Aluminum Alloys of High Strength" in this Handbook.

¹⁴See "Lead Baths," "Salt Baths," and "Cyaniding," in this Handbook.

with the surface of the object some cooler material, which may be gaseous, liquid, or solid. A fine wire or thin sheet will cool rapidly by radiation alone, especially in the high temperature range. Observe, for example, the rapid cooling of the filament in a vacuum lamp when the current is turned off. Heat dissipation by radiation is slow at low temperatures, however, and even at high temperatures is too slow to result in very rapid cooling of any but very thin sections.

The application of a cooler material to the surface of an object to promote rapid cooling is called quenching. This may be by means of a current of some gas, such as air; a spray or jet of liquid, such as water; immersion in a liquid such as water; application of a cold solid, such as cooling (quenching) between plates or in a press; or by combinations of these means.

It is seldom that the cooling medium can be applied to a clean surface of the metal itself, because this surface is usually covered with some sort of scale or oxide film. These nonmetallic coatings have less thermal conductivity than the metals, so they retard cooling. Heating in such a way that oxidation is prevented or minimized is therefore conducive to rapid cooling on quenching.

To produce the most rapid quenching, the cooling medium must be kept in contact with the surface of the metal, and that portion of the cooling medium immediately in contact with this surface must be kept cool. With gases, such as air, there is no difficulty in maintaining close contact. The heat capacity and heat conductivity of air are quite low, however, so very rapid and uniform circulation and large volumes of air are required to keep the air immediately in contact with the surface of the metal cool. Gases are not, therefore, generally suitable or economical for rapid quenching.

Liquids have much higher heat capacities than gases, the specific heat of water in particular being substantially the highest known. The problem of maintaining contact between a liquid quenching medium and the object to be quenched is one of keeping gases from adhering to the surface of the object. These gases may be carried into the quenching medium by the object itself (adsorbed on the surface or trapped in pockets) or may come from the quenching medium by liberation of dissolved gas, such as air in water, or by vaporization of the liquid itself. Gases arising from these sources and adhering to the surface of the object insulate the object from the liquid and thus retard cooling. Circulation of the liquid against the surface helps to remove gases, and also tends to prevent the liberation of gases or vapors from the liquid, by preventing the overheating of the liquid in contact with the surface. By boiling, water can be substantially freed from dissolved air before using it for quenching.

When it is desired to cool certain portions of an object more slowly than the object as a whole, such as holes and keyways, in steel to be hardened, these portions may be shielded from the full action of the cooling medium by the application of clay, asbestos, and sodium silicate, or other insulating material.

The effect of a quenching medium on the properties of a metal depends on the rate of cooling produced. There is no evidence of any magic effect due to the composition of certain local waters, curious aqueous solutions, or odd mixtures of oils which have been used or proposed, except insofar as cooling rate is affected.

It is to be noted, however, that the *average* rate of cooling from the quenching temperature to that of the quenching medium is not a sufficient indication of the effect on the metal. The rate of cooling at all temperatures on the way down must be considered. For example, a certain object made of an alloy tool steel may be found to crack when quenched in cold water for hardening. Slower cooling is indicated, and the object may be successfully quenched in a certain oil without cracking. Equally slow cooling through the higher temperature range may be obtained by quenching in boiling water, but the object may be found to crack. This is because the cooling rate is too rapid at lower temperatures—say from 700-300°F.

The cooling rates imparted by various quenching media to steel, in particular, have been carefully studied.^{17, 18} Detailed data on this and other phases of the art

¹⁷H. J. French and T. E. Hamill, *Hot Aqueous Solutions for the Quenching of Steel*, Trans., A.S.S.T., 1929, v. 16, p. 711.

¹⁸H. J. French and O. Z. Klopsch, *Quenching Diagrams for Carbon Steels in Relation to Some Quenching Media for Heat Treatment*, Trans., A.S.S.T., 1924, v. 6, p. 251.

of quenching will be included in one or more additional articles in the Handbook.

When the ratio of the surface of an object to its volume is large, as in wire and thin sheet, extremely rapid cooling can be obtained by a quenching method which rapidly cools the surface, such as a jet of cold water of ample volume and under high pressure. With heavier sections, however, cooling rate is limited by the rate of conduction of heat from the interior to the surface. Hence, it becomes impossible by any method to rapidly cool the center of a large section of steel. If the composition of the steel is such that rapid cooling is necessary for full hardening, it is then impossible to cool the center rapidly enough for such hardening. This is called the "mass effect."¹⁹

Different quenching media may be used in sequence to produce different rates of cooling. For example, a tool may be air cooled for a short time before quenching in water, to reduce distortion and strains, or a crankshaft of alloy steel may be quenched in water for a measured time and then removed and allowed to cool in air, or transferred to oil, to prevent cracking.

¹⁹See "Mass Influence in Heat Treatment" in this Handbook.

Recrystallization

By R. F. Mehl*

Metals which have been strained by cold working are not stable, but tend to revert to a strain-free state. This article will consider the processes, of which recrystallization is the chief, by which the effects of cold work may be relieved. In order to understand these processes, it will first be necessary to consider the effect of cold work on the nature of metals.

The Nature of Cold Worked Metals—Cold work consists in the plastic deformation of a metal at such temperatures and at such rates that no recrystallization occurs during the deformation process; under such conditions the metal is strain hardened. The compression of iron at room temperature, for example, is cold work; but the compression of iron at higher temperatures in the absence of recrystallization is also cold work. Only when such temperatures are reached that recrystallization (which leads to softening) occurs during the working process, can the term hot work be properly employed; in general, these temperatures are high in metals melting at high temperatures and low in metals melting at low temperatures—occasionally as low as room temperature or below. Since permanent plastic deformation is required, it will be obvious that the deformation must be beyond the yield point.

Such deformation produces fundamental structural changes in the metal. At low degrees of deformation, slip lines appear in those grains in which the slip planes are most favorably oriented for yielding under the resolved shear stress; in metals which readily form mechanical twins, like zinc at ordinary temperatures or iron at low temperatures, twin bands also appear; as the degree of deformation becomes greater, slip lines appear in an increasing number of grains, the grains tend to rotate, the crystal planes to become curved, and the grains to become sensibly elongated in the direction of flow. It is a result of the fact that the directions in the crystal grain by which flow can take place during deformation are determined by lattice symmetry and are therefore not random, that cold (and hot) deformation is accompanied by the generation of preferred orientations, which may be described in crystallographic terms, accompanied by corresponding directional properties. This deformation is accompanied by an increase in the strength properties: Hardness, yield point or strength, tensile strength; and a decrease in the ductility properties: Elongation to fracture, reduction of area at fracture, drawing capacity, impact strength; it is accompanied also by a slight decrease in density, a slight decrease in electrical conductivity, and a decrease in maximum permeability, and by an increase in electrode potential, an increase in coercive force, a slight increase in the coefficient of thermal expansion, and a slight increase in compressibility.

The atoms in an annealed metal are in a continuous state of thermal vibration about mean positions which are symmetrically disposed on a space lattice; apart from relatively minor imperfections, this is a geometrically perfect arrangement. The perfection of this arrangement, however, is grossly altered by deformation: The lattice planes become curved and twisted, atoms no longer have precision mean positions on a space lattice but are distorted to positions less symmetrically disposed, with resultant distortion of atom shapes and energy distribution and increase in the internal energy of the metal.

The nonhomogeneous character of cold deformation creates a pattern of internal strains. In commercial forming operations, the friction of rolls or of dies, or the complexities introduced by multiple types of deformation or by heat treatment, create internal "macroscopic stresses," (Heyn stresses). These macroscopic stresses are characterized by a gross distribution in such a way that one section of a piece may be in tension while another is in compression; thus, for example, the center of a cold drawn copper wire is in compression while the outside is in tension. Furthermore, a pattern of stresses on a fine scale, "microscopic stresses," characterized by minute regions in which tensile (and compression) stresses occur, also are formed as a result of slip on atom planes, of the bending of slip planes, of slip on intersecting slip planes, and of the impedance to normal slip at grain boundaries. Such a pattern of stresses will obviously be characterized by points of unusually high energy peaks, which are the points of least stability in the cold worked metal

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where processes relieving the effects of cold deformation will originate. The greater the amount of cold deformation the greater will be the number of such peaks.

The heating of cold worked metals results in a softening and accordingly a renewed ability to suffer cold work. This heating also relieves both microscopic and macroscopic internal stresses, either of which may be harmful in special cases though generally cold worked materials find widespread and wholly satisfactory applications. Macroscopic stresses can measurably decrease the fatigue strength of materials, can be conducive to failure in stress corrosion as in season cracking, and can lead to the yielding of structural members at loads below the normal yield strength. Any softening process which will obviate these effects is obviously important practically; it will be seen that both the process of recovery and that of recrystallization will perform this task.

The Effect of Annealing on Cold Worked Metals—The changes in properties which follow upon annealing are in the direction of the restoration of the properties obtaining before cold deformation. But the ways in which the various properties change on annealing are not simple.

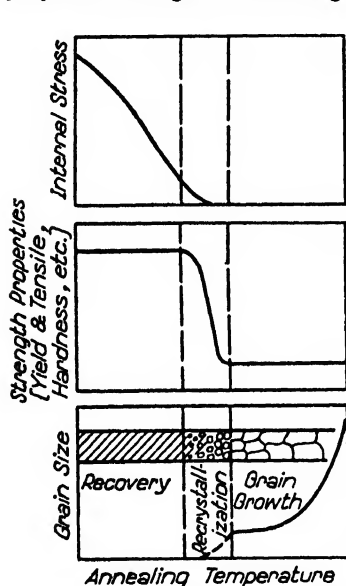


Fig. 1—Schematic representation of recovery, recrystallization, and grain growth (Adapted from Sachs).

Three types of mutually distinguishable processes occur on annealing a cold worked metal. These are: (1) Recovery, (2) recrystallization, and (3) grain growth, as illustrated in Fig. 1. Recovery is a change in the properties, particularly those determined by the state of internal strain, of a cold worked metal at low annealing temperatures that is unaccompanied by any detectable change in the microstructure of the cold worked metal. Recrystallization, occurring at higher temperatures, is a process of the formation and growth of new unstrained grains, supplanting entirely the cold worked structure. Grain growth, occurring in completely recrystallized metals, is merely a continued growth of recrystallized grains.

These three processes are all dependent upon time—they are not instantaneous. The rate at which each operates increases with increasing temperature following an exponential law. When the temperature to which a cold worked metal is subjected is sufficiently high, these processes operate with such rapidity as to appear to be instantaneous, but at lower temperatures the time dependence is readily detected. The rates, however, vary widely from metal to metal and are greatly dependent on composition, purity, grain size of the sample before deformation, and the amount of deformation. Generally speaking, metals with low melting points exhibit high rates at low temperatures, as in the case of tin. Furthermore,

the three processes sometimes overlap and are difficult to distinguish, while in other cases they can be clearly separated. The accompanying changes in properties are not always parallel, that is, the properties do not change concomitantly (Fig. 5), and this fact often permits the production of unusual property combinations.

Recovery, recrystallization, and grain growth are all processes leading to softening. It is conventional to study these by heating cold worked samples to a series of increasingly elevated temperatures and holding for a certain time period, usually between 15 min. and 2 hr., and subsequently measuring the properties at room temperature.

The selection of a constant time period of annealing eliminates time as a variable, and the results must be viewed with this limitation. In a narrow temperature range the change in properties is rapid, as shown in Fig. 2 for copper of various degrees of purity, but this range may readily be displaced to lower temperatures by increasing the time of annealing (Fig. 3); in a rough way, doubling the annealing time lowers the softening temperature by 10°C. The temperature of rapid softening is also decreased by an increasing degree of cold work (Fig. 4).

These curves of softening do not distinguish the three processes described above with absolute certainty. Of the three processes, recovery should be considered first since it is the process which occurs first on heating.

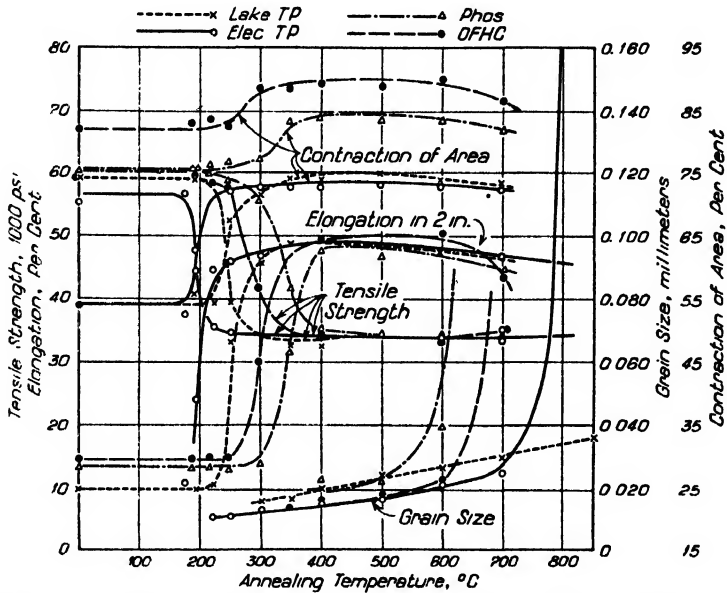


Fig. 2—Effect of annealing on tensile properties and grain size of tough pitch lake, tough pitch electrolytic, phosphorized (0.02% P), and oxygen free high conductivity copper. Wires cold drawn to 62.5% reduction in area and annealed one hour (Pratt).

Recovery—The elongation of single crystals is characterized by a steadily rising stress-strain curve. If the load is removed and immediately reapplied, the stress continues from the point of interruption; if, however, time elapses between release and reapplication of load, or if the piece is slightly heated, the stress begins at a low value, that is, strain hardening has been lost, though no recrystallization has taken place. This is recovery, sometimes termed crystal recovery. The process is most striking in single crystals but occurs also in aggregates.

The effect of recovery in iron on several physical properties is shown in Fig. 5. The Brinell hardness decreases rapidly upon recrystallization, and only a very slight

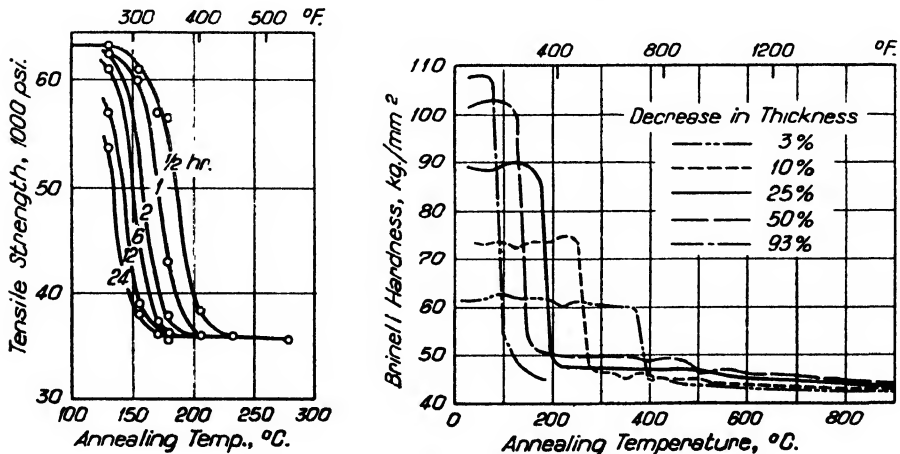


Fig. 3—Influence of annealing time on softening of copper wire, reduced 93% by cold drawing to dia. of 0.26 mm. (Alkins and Cartwright).

Fig. 4—Softening temperature of cold rolled high purity copper in dependence upon per cent reduction of thickness (Köster).

decrease as a result of recovery occurs before this, but the thermoelectromotive force and the electrical conductivity decrease at much lower temperatures, and the change in these is complete before there is any detectable change in grain structure, any recrystallization. This behavior, then, illustrates a change which occurs on heating cold worked metals without recrystallization; it will be seen that the several properties do not change in a parallel way.

Recovery is especially marked in the relief of internal stresses, as shown by the curve for "spring back" in Fig. 5. The tendency to season-crack in brass, the magnitude of macroscopic stresses, and the general tendency to crack on treatment are greatly decreased by annealing to induce recovery without recrystallization; such stresses in cold worked steel can be largely eliminated by annealing at 850°F., at which temperature steel does not recrystallize. Complete stress relief can be more completely attained by annealing to higher temperatures, and this is the usual commercial practice.

The process of recovery in metals is doubtless widespread, though experimental studies have not been sufficiently extensive to say when recovery may be separated from recrystallization and when these two processes overlap. In the latter case, distinction cannot be made. In Fe, Ni, Pd, and Pt, recovery may be readily distinguished from recrystallization, for the changes in properties on heating are not parallel (Fig. 5), but in Cu, Ag, and Au, the properties change more nearly simultaneously upon annealing; whatever may be the underlying cause of these differing behaviors, it may be seen that the type of space lattice is not important, but that the position in the periodic table is.

The causes for recovery are not clear. Recovery is doubtless a change in the internal stresses in worked metals, affecting primarily the elastic properties, and also the electrical, magnetic, and miscellaneous properties like velocity of solution in acids, but having relatively little effect on the strength and ductility properties. This stress removal may be associated with the straightening of bent slip planes, and perhaps with the healing of microscopic cracks adjacent to points of severe curvature of slip planes; it cannot, however, be pictured as a complete relief of stress, but only as a partial relief of some special sorts of stress, for a metal which has recovered does not lose its capacity to recrystallize, and in some cases an entirely undiminished capacity for recrystallization has been demonstrated. The reasons for strain hardening in cold working are not well understood, and until the cold worked condition itself can be more adequately described, it is unlikely that recovery and the types of stresses causing recovery and recrystallization can be more clearly understood.

Recrystallization—On heating a cold worked metal to a sufficiently high temperature, or for a sufficiently long time at a somewhat lower temperature, new grains appear and grow, until ultimately a new grain structure has completely replaced the old. This is recrystallization. The changes in properties which accompany recrystallization are in the direction of the restoration of the properties characteristic of the metal before cold deformation, though these properties may not be exactly reproduced, for the final grain size may be different from the initial. The softening temperatures illustrated in Fig. 2, as shown by the rapid increase in elongation and decrease in strength, are temperatures at which recrystallization occurs, and generally such property changes can be safely taken as evidence for recrystallization, but when the material has partially recovered before recrystallizing, the changes in strength properties do not sharply define the beginning of recrystallization, and when grain growth after recrystallization is pronounced the

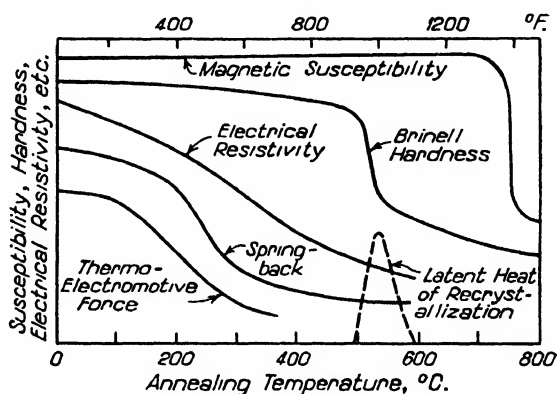


Fig. 5—Recovery and recrystallization in iron. Annealing time one hour; cold rolling 95-98%. "Spring back" is the increase in dia. of a roll of strip after removing from mandrel about which it had been held (Adapted from Tammann).

strength properties continue to change after the completion of recrystallization and thus do not sharply define the completion of recrystallization; in such cases microscopic studies are required to define the beginning and the ending of recrystallization though frequently X-ray diffraction methods are much superior.

The complete removal of the effects of cold work and the possibilities of controlling grain size, and thus particularly the behavior of the material toward further working, make recrystallization a process of immense practical importance. Unusually large grains are often highly undesirable, for they lead to an unattractive rough appearance of drawn objects (for example, the familiar "orange peel" effect), and to tears in large worked sections. It is therefore of the greatest importance to know what factors govern the temperatures and times of recrystallization and what factors govern the final grain size.

The process of recrystallization is one of the continuous formation of nuclei of new crystals and the growth of these nuclei until the system is wholly constituted of the new grain structure. The rate of formation of nuclei and the rate of growth of these nuclei are thus the basic factors determining the rate of recrystallization, and it is necessary to inquire how these may vary with temperature, with time, with initial grain size, with degree of deformation, and with composition and purity.

Recrystallization is thus not an instantaneous process but one with a clearly apparent time dependence. It is in this sense entirely similar to the formation of pearlite from austenite, giving rate curves of a completely analogous form. Most recrystallization data, however, have been obtained by employing short and fixed annealing times, as stated above, and thus give no clue to this time dependence.

The new nuclei appear to prefer to form at grain boundaries, slip lines, deformation markings of various sorts, and twinning planes, as may be seen in slightly deformed samples, though this is probably also true in heavily deformed samples. Recrystallization can thus most conveniently be detected metallographically, but the sharpening of X-ray diffraction spots and the appearance of new sharp spots can be and has frequently been used as a trustworthy criterion. The mechanical properties are not always trustworthy, as stated above.

Apart from composition and purity four factors determine the grain size after recrystallization: (1) The amount of cold deformation, (2) the temperature to which the cold worked metal is heated, (3) the time for which the metal is held at this temperature, and (4) the original grain size.

Several fundamental laws of recrystallization are now well recognized: (1) Recrystallization occurs at a higher temperature the smaller the degree of deformation or, more accurately, the smaller the degree of strain hardening. (2) Increasing time of annealing displaces recrystallization to a lower temperature. (3) The final grain size is chiefly dependent upon the degree of deformation and to a lesser degree on the annealing temperature; the final grain size is the larger the smaller the degree of deformation. (4) The larger the original grain size the greater the amount of cold deformation to give equivalent recrystallization temperatures and times. In addition to these major factors, it should be noted that (a) the rate of heating to the recrystallization temperature is a further variable, and (b) the amounts of cold work to give equivalent strain hardening vary with the temperature at which deformation is performed.

The first law may be illustrated by a diagram in which the beginning of recrystallization is plotted against annealing temperature for cold worked iron (Fig. 6). Here it may be seen that recrystallization does not occur below 460°C., and that the temperature of beginning recrystallization increases with decreasing deformation

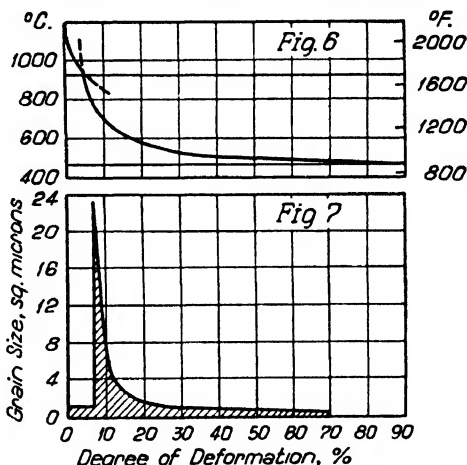


Fig. 6—Curve of initial recrystallization of low carbon steel in dependence upon temperature and degree of deformation at temperature (Hanemann).

Fig. 7—Grain size developed at 950°C. in low carbon steel in dependence upon degree of deformation (Hanemann).

until the A_1 temperature is encountered. This diagram, obtained for deformation at the temperature of recrystallization, differs from a diagram for deformation at room temperature and recrystallization at the designated temperature only in degree—the general form is the same, as indeed it is for all metals and alloys. Therefore, for degrees of deformation and annealing temperature to the left of and below the curve of beginning recrystallization, no recrystallization occurs, no change in the grain structure can be detected; in this range recovery occurs.

The exact position of such a curve will vary with a number of factors, with the type of deformation, with the original grain size, and with purity. Even slight differences in purity exert a wholly disproportionate effect. Data on recrystallization are given elsewhere in this Handbook; see, for example, the article on the Effect of Cold Work on the Properties of Iron, and other articles on the properties of various metals and alloys. It is ordinarily difficult to determine the applicability of published data to a given material, for frequently important variable factors have been disregarded, especially in the older publications.

The grain size developed on heating samples which have been deformed to increasing degrees is especially instructive (Fig. 7). Here we see that a deformation of approximately 7% is required before any change in grain size occurs; this degree of deformation, at which grains suddenly grow to a large size, is known as the critical deformation.

The formation of large grains on recrystallization at the minimum deformation is probably caused by the occurrence of a minimum of recrystallization nuclei; at degrees of deformation below this the number of recrystallization nuclei becomes disappearingly small. With increasing degrees of deformation, an increasing number of points of high stress (high energy) are present, leading on recrystallization to a greater number of nuclei and finally to a greater number of grains and thus to a continually smaller grain size.

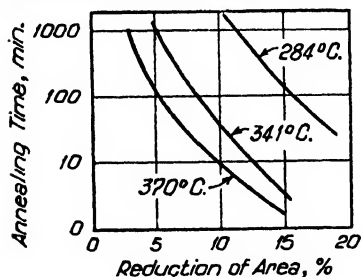


Fig. 8—Influence of degree of deformation and time of annealing upon recrystallization temperature of copper deformed by elongation in tension (Adapted from Sachs).

The influence of degree of deformation on the recrystallization temperature and time is illustrated in Fig. 8. This figure shows that for a constant annealing temperature shorter times are required for recrystallization at higher degrees of deformation, and shows also that with increasing temperatures lower degrees of deformation and shorter times are required for recrystallization. Such generalizations are applicable when the type of deformation is simple, as, for example, increasing amounts of compression, but when several types are superimposed, or when reversed deformation occurs—alternate compression and elongation, bending and unbending—the recrystallization tendency is decreased even though reversed deformation may continue to work harden. The reason for this is not clear.

The effect of original grain size on recrystallization can readily be understood. The amount of strain hardening which a given amount of compression, elongation, or torsion introduces into a metal increases as the grain size decreases. When, in a given metal at a single temperature, equivalent amounts of strain hardening are introduced, requiring large amounts of deformation for large grained metals and small amounts of deformation for small grained metals, the recrystallization behaviors are apparently identical.

The relationships between degree of deformation, annealing temperature, and resultant grain size have frequently been assembled into a three dimensional chart, of which Fig. 6 and 7 are sections. Such a diagram for iron is given in the article on the Effect of Cold Work on the Properties of Iron in this Handbook. Charts of this sort are commonly derived from data obtained using constant (and short) annealing times, and do not show the time variable; furthermore, the factor of original grain size is not represented. A five dimensional chart would be required to show all of these relationships. This limitation of three dimensional diagrams, the occasionally extreme effects of minor amounts of impurities, and the complications introduced by the complexities of industrial forming processes with resultant complexities in internal stress distribution, render such charts of little direct practical use. They should be used only to indicate the recrystallization behavior of a material in a qualitative way.

Recrystallized metals, like cold worked metals, can exhibit preferred orientations and directional properties, though they may not be identical with those which characterized the cold worked metal before recrystallization. Relatively little is known concerning the inheritance of preferred orientations during recrystallization, and no generalizations can be made.

Impurities in solid solution exert a pronounced effect upon recrystallization temperatures. The relatively minor variations in composition in the several varieties of copper represented in Fig. 2 may be seen to have caused a difference of 100°C. in the softening temperatures, and more extreme cases have been noted. Increasing concentrations in solid solution become increasingly less effective until, in a completely isomorphous system a maximum recrystallization temperature is reached at an intermediate composition, which may be several hundred degrees Centigrade above those of the component metals. It has frequently been stated that impurities which do not form solid solutions have little effect on softening and recrystallization temperatures; this generalization is somewhat doubtful, for at least in the case of aluminum alloys such impurities are employed to raise the temperatures required for recrystallization, and when present in a sufficiently fine state of subdivision are more powerful in this respect than elements in solid solution.

Grain Growth—Fig. 2 shows softening and recrystallization to have been completed at 400°C., but shows also an increasing grain size on heating beyond this temperature. This growth of grains in an essentially completely recrystallized and strain free structure is known as grain growth. It proceeds in an endeavor to decrease the grain boundary area and thus the internal energy. Grain growth proceeds by the absorption of grains, in the usual case of smaller by larger grains, and doubtless accompanies and overlaps recrystallization at least to some degree. It is especially noticeable following the recrystallization of severely deformed aggregates, for the grain size after recrystallization in this case is small and grain growth is readily noted, whereas in samples recrystallized after slight deformation the grain size is large and the subsequent grain growth is minor. Slow heating favors the growth of large grains, which in some cases may become very large.

Impurities in solid solution have a minor effect on grain growth, but undissolved impurities exert a pronounced effect. With very pure substances grain growth proceeds steadily, with the average grain size increasing with increasing annealing temperature (Fig. 2). But if undissolved impurities, such as ThO₂ in tungsten, iron in aluminum, lead in zinc, are present in the proper amount, the grain size is then small at low temperatures and suddenly increases in a narrow temperature range forming unusually large crystals; when the amounts are larger grain growth may be entirely obviated. Thus immiscible impurities may be used either to suppress grain growth at relatively low temperatures or to create unusually large grains at higher temperatures.

Bibliography—The bibliography on recrystallization is extraordinarily voluminous, and it is unnecessary to reproduce all of it here and useless to reproduce only selected references. The most complete summaries are those given by G. Sachs, "Praktische Metallkunde, v. II, Spanlose Formung", Julius Springer, Berlin, 1934; and E. Schmid and W. Boas, "Kristallplastizität", Julius Springer, Berlin, 1935. Sachs gives a complete summary except for iron and steel, while Schmid and Boas stress the scientific aspects of the subject. Data on the recrystallization of iron and steel may be found in P. Oberhoffer, W. Eilender, H. Esser, "Das Technische Eisen", Julius Springer, Berlin, 1936; and E. Houdremont, "Sonderstahlkunde", Julius Springer, Berlin, 1935. The material in the present paper has been drawn largely from these sources. An extensive bibliography on the recrystallization of iron and steel has been given by H. F. Kaiser and H. F. Taylor: "The Effect of Cold Deformation on the Recrystallization Properties of Armco Iron," American Society for Metals, preprint, 1938 fall meeting.

The Relation of Design to Heat Treatment*

Design bears in many ways upon the serviceability of a tool or machine part, and unsatisfactory performance may frequently be traced directly to faulty design. This report is concerned only with design as it affects the heat treating operation—and through the heat treatment, the serviceability of the finished parts. It is the purpose of this report to bring about a better mutual understanding between the designer and the steel treater so that faulty design which may cause cracking, or distorting, during heat treating can be avoided.

The fundamental principles of good design from a heat treatment standpoint are quite simple. Heat treated steel has a certain strength depending upon the analysis of the steel, the quality of the metal, and the heat treatment which it has received.

When subjected to a combination of forces beyond its ultimate strength, the steel cracks or fails. There are two types of force combining to break the steel: 1. The internal strains set up during fabrication and heat treatment of the part; 2. The external forces of service. Sometimes the internal strains alone exceed the strength of the metal and the part cracks in hardening. Again, the internal strains may equal 90% or more of the total strength, in which case failure will develop in service under relatively light loads. It, therefore, appears that the useful strength of a part decreases in proportion as the internal strains increase.

Internal strains arise from many causes, but the most serious, by far, are those developed during quenching, by reason of differential cooling. This differential cooling (or more accurately "temperature gradient"), is largely a function of the size and shape of the piece being quenched, in other words, the design. Here, then, is the relation of design to heat treatment, and the basic principle of successful design is to plan shapes which will keep the temperature gradient throughout a piece at a minimum during quenching.

Temperature gradient is the rate of variation in the temperature of metal over a given unit distance.

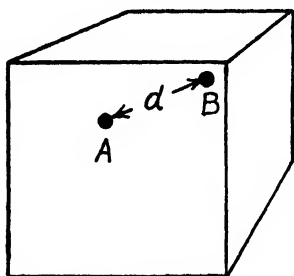


Fig. 1—This cube illustrates what is meant by temperature gradient.

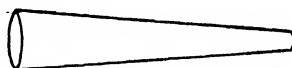


Fig. 2—When quenched, the point of this tapered pin will cool faster than the heavier section.

Fig. 1 may be taken to represent a steel cube interrupted during the process of quenching. Consider the points A and B separated by a distance "d". If, at any given instant during the quench, A is 700°F. and B is 300°F. and "d" equals 1 in., the temperature gradient between these two points is 400°F. per in. If the points are only ½ in. apart, the gradient is said to be twice as steep.

Some shapes are almost impossible to harden because of the abruptness in the change of section, but a certain latitude in design is recognized when using an oil hardening or air hardening steel. All things being equal, the gradient between A and B, in Fig. 1, will be much less in oil than in water, and will be less

*Prepared for the Subcommittee on Relation of Design to Heat Treatment by Frank R. Palmer, Carpenter Steel Co. The membership of the subcommittee was as follows: A. H. d'Arcambal, Chairman; F. R. Palmer, H. J. Stagg, G. M. Eaton, W. H. Wills, A. L. Boegehold, and F. T. Quinlin.

in air than in oil. Thus, a certain design may be perfectly safe for one kind of steel, or one type of coolant, and unsafe for another.

Errors in design reach farther than merely affecting the internal strains during hardening. A sharp angle serves to greatly concentrate the stresses of service, and the design of the part may be entirely responsible for concentrating the service stresses at a point already weakened by internal strains produced during hardening. Design errors of this type are illustrated in Figs. 7, 14, 15, 23, and 24. Concentration of service stresses frequently parallels concentration of heat treating strains and is frequently caused and cured by the same combination of circumstances.

Reducing all the above to a single statement, a part is properly designed, from a standpoint of heat treatment, when the entire piece may be heated and cooled at approximately the same rate during the heat treating operation. Perfection in this regard is unattainable because, even on a sphere, the surface cools more rapidly than the interior. The designer should, however, attempt to so shape his parts that they will heat and cool as uniformly as possible. The greater the temperature difference between any two points on a given part during quenching, and the closer these two points are together, the greater will be the internal strain and, therefore, the poorer the design.

There are really not many possibilities for subdividing this main thought. Almost every failure due to improper design can be attributed directly to a violation of the fundamental principle. Some general cases may, however, be considered.

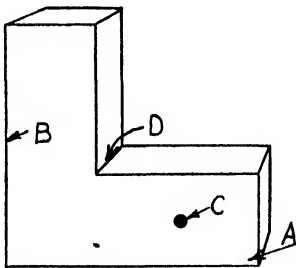


Fig. 3—This illustrates the manner in which the different positions of a piece will cool when quenched.

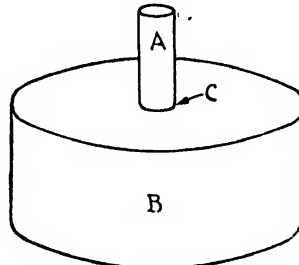


Fig. 4—A light section adjoining a very heavy section.

Effect of Shape on Cooling Speed—When a piece of steel is removed from the hardening furnace preparatory to quenching, it is presumably at a uniform temperature. As soon as quenching begins, the temperature is different in almost every part of the section. This difference in temperature is due to two conditions. In the first place, the heat capacity or heat storage may be greater in one part of the section than in another, due simply to the fact that there is more metal in one part than in another. This is illustrated simply by a tapered pin, as shown in Fig. 2. Obviously, the point of this pin will cool faster than the heavy section, because there is less heat to be dissipated per square inch of cooling surface.

The rate of cooling is also affected by the shape of the surface. Fig. 3 illustrates a piece which is quite uniform in cross section, but which will not cool uniformly. The protruding corners, such as A, are cooled from three sides so that the extreme corner is giving off heat from approximately seven times as great an area as it is receiving heat. An edge, such as B, is cooled from two sides and is giving off heat through three times as great an area as it is receiving heat. A point on the flat side, such as C, receives heat from one side and delivers it from the other, and the cooling area and the heating area are approximately equal.

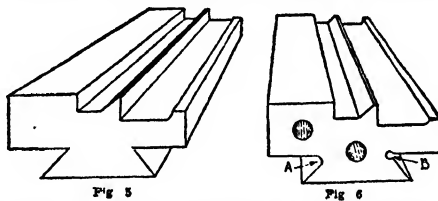
At a re-entrant angle, such as D, heat is being supplied to the surface through three times as great an area as it is being dispelled, and this point will naturally cool last. Sharp re-entrant angles are always objectionable from the standpoint of design. It is impossible to get uniform cooling during the quench in the immediate neighborhood of a sharp angle. Vapor pockets will frequently form in the corners and produce an actual soft spot. Even if no soft spot is formed, the rate of cooling

at the point of the angle is bound to be slow, because the corner is so inaccessible to the coolant. Differential cooling thus sets up heavy internal strains at a point which is almost certain to receive concentrated stresses in service.

It will be seen from the above that it is possible for one part of a section as shown in Fig. 3 to cool many times faster than another part.

If we have a section as shown in Fig. 4, we have a combination of the conditions given in both previous illustrations. The heat capacity of the body "B" is much greater than the projection A, and we have a sharp re-entrant angle at point C. It would be practically impossible to harden such a shape in water without cracking at the sharp corner. Even oil quenching would be doubtful on a piece of these proportions, and only by cooling in air could we expect to keep the thermal gradients down to a safe point (where the design is such that there is danger of cracking, air quenching should be used). A few practical illustrations are given in Figs. 5 and 6 to illustrate the above principles.

Fig. 5 illustrates an under-cutting form-tool. It will be noticed that the cross section of this tool is made up of heavy and light sections joined together with



Figs. 5 and 6—An under-cutting form-tool showing methods of dealing with heavy and light sections. Fig. 5 shows incorrect design and Fig. 6 shows correct design.

sharp re-entrant angles. A tool of this shape would be extremely hazardous to harden either in a water hardening tool steel or a high speed steel.

A corrected design for the above tool is illustrated in Fig. 6. Holes have been drilled through the two heaviest sections, and thus the weight of the metal has been fairly well balanced throughout the cross section of the tool. The sharp angles on the cutting edge cannot be eliminated because they are a part of the form of the tool. Two suggested treatments are shown for the angle at the base of the dovetail. The best treatment is shown at A, where a generous fillet is provided. An alternative is shown at B, where the corner has been under-cut to provide a radius and still give the effect of a sharp corner. From a standpoint of quenching strains, the under-cut form at B has little to recommend it, but it does have the advantage that there is no absolutely sharp corner in which the stresses can accumulate.

Fig. 7 illustrates a case of improper design in a double ended side-mill or spot-facer. Each side of this tool has three teeth with the teeth placed opposite to each other. This is a badly balanced condition in the cross section of the piece and is made more serious by a sharp corner at the base of the teeth. Such a tool is almost certain to crack at the junction between the light and heavy sections. This condition may be corrected by staggering the teeth on opposite sides of the tool and introducing a generous fillet at the base of each tooth.

Fig. 8 illustrates two principles of design. This is a ring shaped section containing two keyways on opposite diameters. The keyway A is shown with absolutely sharp corners. This is never good design, and while millions of keyways are being made and used with sharp corners, this does not alter the fact that it is poor design, and every effort should be bent toward making standard a round cornered keyway such as is shown at B.

The second interesting point about this ring is that when it is quenched it will not stay round. The section of the ring is weakened through the two keyways, and almost invariably the ring will become oval. This condition may be corrected by cutting in two more keyways at 90° to the first two, as is illustrated in Fig. 9. These keyways may be of no use but they certainly do no harm, and their presence will balance the section and keep it round.

Another example of a shape which will almost certainly warp during heat treatment is shown in Fig. 10. Let us assume that this is a blanking die. Even though

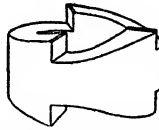


Fig. 7—Improper design for a double-ended side-mill or spot-facer. This shows an unbalanced condition and sharp corners at the base of the teeth. (Only upper half of tool shown.)

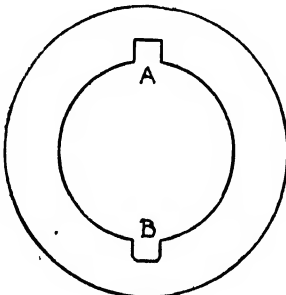


Fig. 8

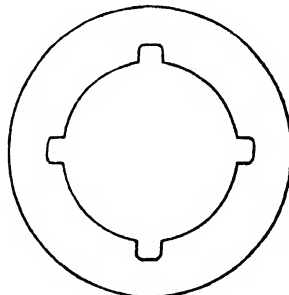


Fig. 9

Fig. 8—Correct and incorrect type of keyways. Sharp corners at "A" are incorrect design, while the rounded corners at "B" are correct. Fig. 9—Method of balancing keyways to avoid warping.

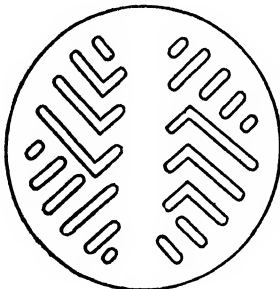


Fig. 10

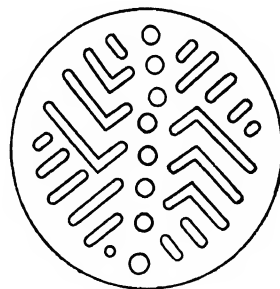


Fig. 11

Fig. 10—A blanking die with center rib heavier than the surrounding areas, which often causes warping when quenched. Fig. 11—A similar die with holes drilled in the middle rib to equalize the amount of metal throughout the die, thus eliminating warpage difficulties.

this piece was made from an oil hardening, nonchanging, tool steel it would warp during quenching. The rib through the center would tend to prevent shrinkage in this direction, and the die would become oval. This figure is intended to illustrate a principle, and it is surprising how often it comes up in actual design. Certain portions of a die are held rigid by a web, while adjacent portions are unsupported, and warpage or distortion occurs during hardening which cannot be avoided without resorting to an air hardening steel. Frequently it is possible to avoid the difficulty due to such a rib by drilling holes, as illustrated in Fig. 11. Holes drilled for such purposes should always be of such size and so located as to help balance the section, rather than to unbalance it. Success in preventing warpage, and other forms of internal strain, will be directly proportional to success in balancing the weight of the sections and producing uniform cooling conditions.

Large dies of intricate design are sometimes made up in sections which often simplifies the problem of heat treatment.

To further illustrate the principles covered above and to assist in avoiding faulty design, Figs. 12-22 are given. Each illustration depicts one or more errors of design which is explained in the caption together with the danger encountered.

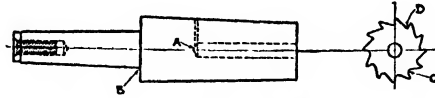


Fig. 12—A large reamer. When quenched the stresses will concentrate at the junction of the two holes at "A". Blind holes are poor design. Such holes should be continued throughout the entire length. A good fillet should be used at "B" in order to eliminate cracking from the sharp corners during hardening. The roots of the cutters should have good fillets as shown at "C" instead of the dangerous sharp angle at "D"

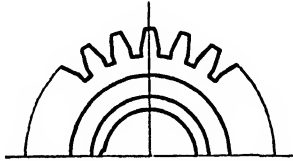


Fig. 13—A gear burnisher from which teeth were broken during hardening because practically no radius was provided at the roots of the teeth.

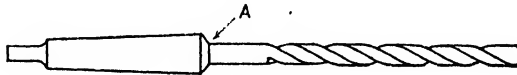


Fig. 14—Twist drills of this design gave considerable trouble in service from breaking at "A". When a more generous fillet was allowed, the trouble encountered was eliminated.

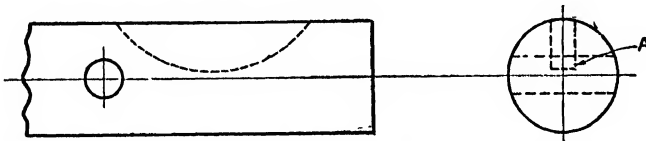


Fig. 15—A stem pinion with a keyway about one-half the diameter of the stem. The base of the keyway is extremely sharp, as shown at "A". The piece is further weakened by a hole drilled through the center of the stem near the keyway.

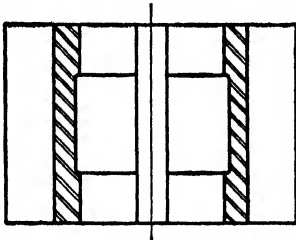


Fig. 16

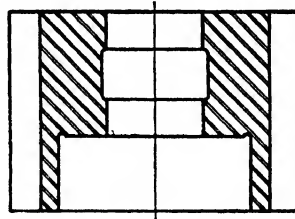


Fig. 17

Fig. 16—A gage with the hole out of proportion to the outside diameter. This will cause the piece to go out of round or into barrel shape when quenched. Fig. 17—A cutter with the counter-bore too large for the design, which will cause the front end of the cutter to close in when treated.

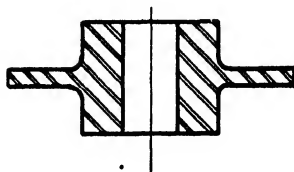
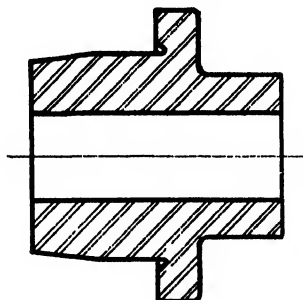


Fig. 18—A dangerous design consists of thin collars adjoining thick sections. When hardening pieces of this design, the thin sections often crack from the hubs.

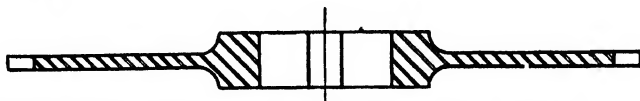


Fig. 19—A cutting tool with a very narrow cutting edge with a thick hub. When quenched the cutting edge will often warp or buckle.



Fig. 20—This shows the theoretical sharp points on cutting tools. These sharp points will burn off in hardening. They should have a small flat surface as shown at "A".

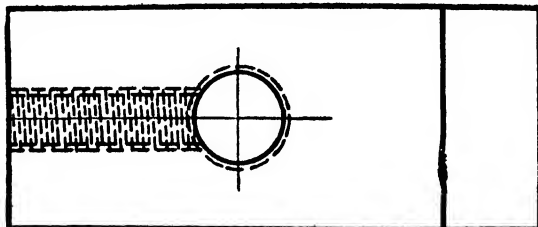


Fig. 21—When hardening, the concentration of strains at the junction of the two holes in the center will cause failure. Such holes should be plugged before hardening.

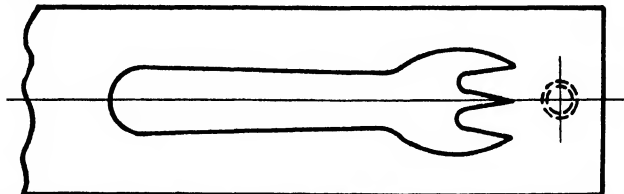


Fig. 22—A blanking die poorly designed. Crack will occur from point of fork prong to set screw hole. The position of the set screw hole should be changed to eliminate cracking.

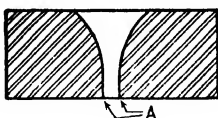


Fig. 23—Longitudinal section of a cold drawing die. Stresses set up in heat treatment and in service concentrated at point "A" so a fillet should have been used to avoid chance of spalling at corners.

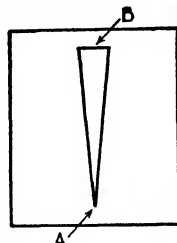


Fig. 24—Blanking die (oil hardening) from approximately a 3 x 1/2 in. section. Stresses set up in heat treatment and in service concentrated at points "A" and "B". A slightly larger section such as 3 1/2 x 3/4 in. probably would have eliminated failure.

Welding of Metals*

Scope—This article is intended to cover principally the metallurgical aspects of the art of fusion welding and also certain allied processes. With recent developments in fusion welding processes, this art has assumed a prominent place in industry and is being extensively used in the preparation and shaping of metal parts, and their fabrication into engineering structures. It is not the purpose of this article to go deeply into the detail of the technique or equipment involved in the application of the various processes, but attention will be focused on the essential elements for satisfactory welding, as well as also the inspection methods and testing procedure that are necessary for determining weld quality. Brief attention is paid also to the subject of safe practices as it concerns certain of the welding processes.

Fusion Welding—Definition—A weld may be defined as a localized union or consolidation of metals. While the several welding processes involve other factors in addition to the application of heat, the importance of the effect of heat in all practical welding operations should be recognized.

Welding as embraced in the scope of this article is usually employed to unite like metals for purposes where the union or joint will be called upon to develop strength and transmit stress. The above definition is broad enough to include certain subsidiary processes such as bronze welding and hard facing which involve unlike metals, although low temperature soldering will not be covered.

General Consideration—The metallurgical, chemical, physical, and thermal characteristics of the metals greatly influence their weldability. The weld has been defined as "a localized union or consolidation of metals." There are a number of processes whereby this "localized union" can be accomplished but all processes, now in general use, have three characteristics in common. First, the "union or consolidation" is localized; second, the metal in the joint must be heated above the critical point; and third, the weld is accomplished in a comparatively short period of time and frequently in a progressive manner. Thus a small volume in a large mass of cold metal is, in rapid succession, heated from room temperature to above the critical point and cooled to below a black heat again.

In fusion processes the temperature frequently goes well above the melting point and all temperatures within the indicated range are present at the same time in bordering zones. In addition to thermal changes, such as expansion and contraction, metallurgical effects such as crystallization and heat treatment, chemical reactions, and changes in physical characteristics, such as strength and ductility, throughout the temperature range required by the process, must be considered.

The simplest phenomenon which happens to metals on heating is, of course, expansion. This, in the initial stages, is purely a change of volume and in most metals is a completely reversible change regardless of the rate of heating or cooling. At the same time that they are expanding, most metals become increasingly soft, ductile, and weak, a fact that is an advantage and a disadvantage. Due to this fact stresses become dissipated and advantageously spread over the heated area because of the ease with which the metal can stretch and yield. On the other hand the low strength at these elevated temperatures makes it necessary to be certain that the piece being welded is free to move so that an undue load will not be placed on the hot metal. Some metals become so weak that it is necessary to support them to prevent buckling or change of shape.

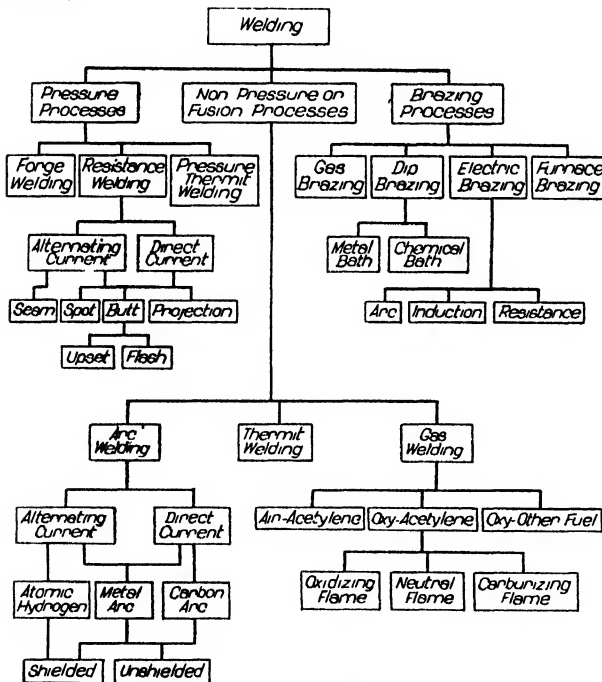
Particular attention must be paid to the final weld of a closed structure or in joining a light to a heavy section in order to reduce the internal stress in the structure to a minimum. Metals having a high rate of thermal conductivity present a particular problem in this respect since the heat is generally spread over a wider area and thus the expansion is greater, also such metals generally have a much greater reduction in strength on heating and frequently require support to prevent buckling.

*This article was prepared under the sponsorship of the International Acetylene Association, who appointed a special committee to handle the work. The International Acetylene Association felt that in order to do full justice to the subject, they should invite electric welding experts and users to join their committee. The full membership of the committee was as follows: C. W. Obert, Chairman, The Linde Air Products Co.; E. V. David, Air Reduction Sales Co.; L. D. Meeker, General Electric Co.; E. W. F. Smith, Lincoln Electric Co.; A. G. Wikoff, Union Carbide Company; C. H. Jennings, Westinghouse Electric & Mfg. Co.; H. L. Maxwell, E. I. du Pont de Nemours & Co., Inc.; and W. L. Warner, Watertown Arsenal.

Most common metals react with oxygen of the atmosphere. At higher temperatures the rate of oxidation increases rapidly. Nitrogen from the air also reacts with some metals forming nitrides which tend to increase the strength and reduce the ductility. This condition can be prevented by protecting the molten metal from contact with the atmosphere.

Because of the relative rapidity with which weld metal cools, consideration must be given to the effect of gases, either dissolved or entrapped, in the molten weld metal. In order to insure sound weld metal, free from porosity, the molten metal must be freed of these gases before it solidifies.

The fusion welding processes involve metals under the effect of heat and therefore are subject to the same thermal, chemical, physical, and metallurgical manipulations commonly known in the manufacture of metals. In steel welding, for example, the weld is in some respects a steel casting made in a steel mold and the metal of this casting comes either from the steel mold itself or from a combination of it and the welding rod or electrode. In gas welding the heat is applied to both the mold and the rod from external sources. In arc welding the heat results from electrical energy which passes through both the electrode and the mold. The welding processes are shown in the following chart prepared by the *American Welding Society*:



Pressure Welding Processes

Forge Welding—This is the oldest process of welding and is the only one whose general practice antedates the twentieth century. It is essentially a process of joining metal pieces that have been heated at the place of joining, to a condition that approaches plasticity on the surface. As soon as the plastic condition is reached the parts are quickly superimposed and worked into complete union either by hammering or pressure. The hammering is performed either manually or by machine and the force of the hammering or pressure is dependent largely upon the size and mass of the pieces or parts being joined.

Resistance Welding—

General—In this process of welding, the surfaces to be joined are heated to

the plastic condition by the passage of a heavy localized electric current accompanied by mechanical pressure to bring the parts into complete union. To produce the required heavy current at low voltage, the employment of alternating current has been found most convenient as it is possible by the use of suitable transformers to obtain almost any desired combination of current and voltage. Only in special cases is direct current used for this purpose.

An important feature in all resistance processes is the composition of the electrode, which must possess good thermal and electric conductivity combined with maximum hardness and sufficient strength. A combination of these requirements has been achieved to a high degree by the use of a hard copper electrode faced with one of several alloys whose hardness under welding conditions is much greater than that of copper.

Resistance—Butt Welding—In the butt welding form of the resistance process, pieces are mechanically gripped and pressed together while heat is generated by

passing a large electric current through the area of contact. The original upset method is a form of butt welding in which high mechanical pressure is applied and maintained throughout the operation, the temperature being kept below melting. The extruded metal is upset into a roughly convex form which, if desired, may be molded to a predetermined shape in a die, thus securing a kind of drop forging, or it may be ground off. Today the upset method is generally combined with flashing. The flash method as first developed is a form of butt welding in which, after initial contact and heating, there is a brief period during which the parts are slightly separated, thereby causing intense arcing. The weld is then completed under pressure and at a temperature sufficient to bring to a plastic state a portion of the metal, part of which is extruded in the form of a thin burr which may be ground off. This method is still followed on large work, but on smaller work the flashing effect, which in the original process was secured by separation of the parts, is obtained by an automatic successive adjustment of pressures. There is no hesitation in the cycle and as a result this form of flash welding is quite rapid.

Resistance—Spot Welding—In the spot welding form of the resistance process, two or more sheets of base metal are held between metal electrodes which pass a large current of fairly low voltage through the sheets. Immediately following this, and with current maintained, the electrodes are forced together with sufficient mechanical pressure to unite the surface of the sheets in a spot whose size is approximately that of the end of the electrodes; this pressure is maintained until after the current has been cut off.

Resistance—Projection Welding—Projection welding is a form of resistance welding wherein small projections are formed on one or both pieces of base metal. The projections serve to localize the current.

Resistance—Seam Welding—The seam welding form of the resistance process is a series of overlapping welds. Two or more sheets of base metal are usually passed between electrode rollers, which transmit the current and also the mechanical pressure required to produce a welded seam. A current interrupter is generally used for this type of weld.

Resistance—Percussion Welding—The percussive methods of resistance welding differ from the usual forms of resistance welding in that (1) a direct current supply is essential; (2) there is a sudden discharge of electrical energy at the junction, with an arc, which is extinguished by a percussive blow; and (3) the surfaces united are partially fluid. The energy may be supplied by either the discharge of a condenser (electrostatic) or transformed by the collapse of a magnetic field (electromagnetic).

Thermit Pressure Welding—This is another plastic welding process and it differs from the forge and resistance welding processes principally in that the heating to plasticity is obtained from the thermit chemical reaction rather than from fire or electric current.

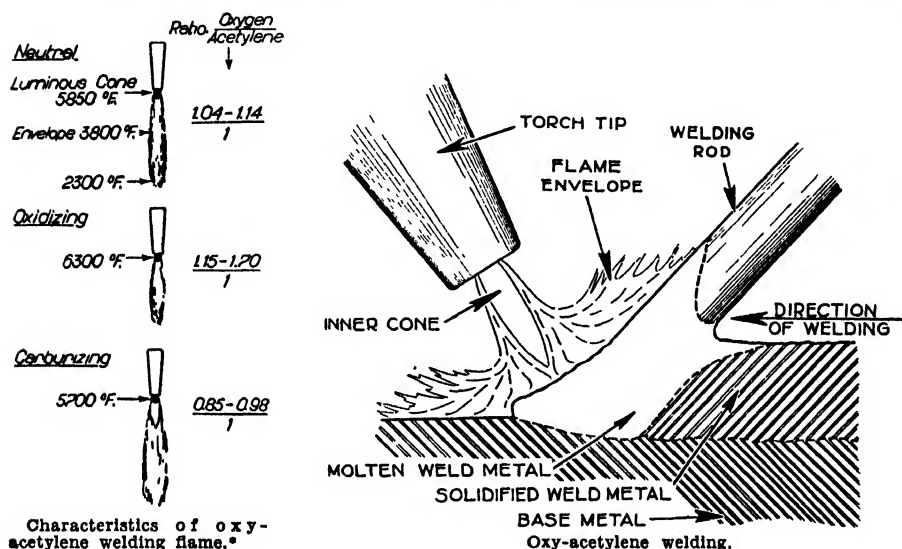
The chemical reaction which generates the required heat for welding is described later in this article under the heading "Thermit Welding." The molten steel and alumina slag are conducted around the abutting ends to be welded in such a manner as to localize the heating, as near as possible, at the joint. This requires the use of a suitable mold, which is usually made of light cast iron segments, which can be clamped in position and then easily removed after the thermit reaction. This thermit reaction is so handled that the alumina slag enters the mold first and leaves a coating on it and the ends being joined, thus protecting these parts from the superheated iron. The passage of the iron through the mold brings the work up to welding temperature in a short time which varies from a few seconds to several minutes, depending on the size.

Fusion Welding Processes (Nonpressure)—These processes differ from the three previously enumerated in that they depart from the union of plastic metals and utilize fusion of metal to effect the desired union. The joining is accomplished by the fusion of metal upon or between the surfaces of the parts being united, the fused metal being generally obtained by deposit from an external source, although in some instances the abutting edges are merely fused together to form the joint.

Gas Welding—In this process the heat is supplied by the combustion of a suitable fuel gas with atmospheric or pure oxygen. The fuel gas and oxygen are mixed in a suitable torch and so regulated as to produce an impinging flame having the desired characteristics. The gases most commonly used are oxygen and acetylene although hydrogen and other combustible gases are used to some extent.

Oxy-Acetylene Welding—Oxy-acetylene welding is a form of fusion welding wherein the heat required is supplied by the oxy-acetylene flame. Usually in fusion welding a filler metal is added in the form of welding rod to form the welded joint, although joints in some instances are formed in oxy-acetylene welding merely by fusing together the parts to be joined without the addition of welding rod. As a means of floating out impurities or aiding in obtaining a satisfactory bond, flux is employed in the welding of some metals, such as cast iron, certain alloy steels, and the nonferrous metals.

In the combustion of acetylene and oxygen the resulting flame has characteristics which indicate whether it is reducing or oxidizing in character. If the acetylene and oxygen are in proportion, a neutral flame results. In most gas welding the neutral flame is recommended, but in certain welding applications, however, a



slightly carburizing or slightly oxidizing flame is considered desirable. Certain of the alloy materials are welded to advantage with a slightly reducing or carburizing flame and under certain conditions a reducing flame is considered desirable in the welding of steel materials.

An important characteristic of the oxy-acetylene flame lies in the protection of the molten metal from atmospheric attack by the outer envelope of the flame. The surrounding oxygen at this point is consumed in the final combustion stage of the flame.

Arc Welding—In arc welding, the surfaces to be joined are fused by the heat of an electric arc. There are three forms of arc welding, each of which derives its name from an identifying element of the process of applying it, such as the electrode material used or the means of heat transfer. They are carbon arc welding, metallic arc welding, and atomic hydrogen arc welding.

Welding current for carbon arc welding is always from a direct current source. Metallic arc welding utilizes either direct or alternating current. Atomic hydrogen arc welding generally is done with alternating current. Direct current for arc welding is usually obtained from a motor generator set. The generator may be of either the variable-voltage single-operator type or specially designed constant-voltage multiple operator type with suitable controls. Rectifier units are also used for this purpose. For alternating current two methods are used: (1) The static transformer, which is a single phase unit specially designed for arc welding. Various methods of control are used, but all are of variable-voltage single-operator type; and (2) The

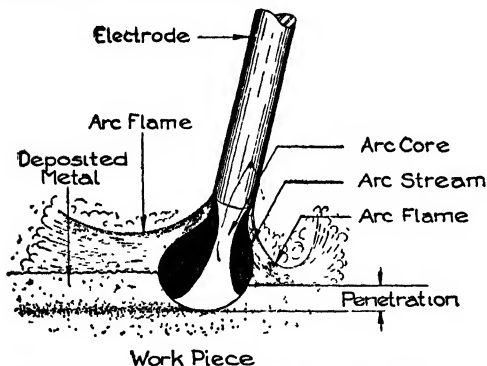
*For complete combustion of acetylene, 1 molecular volume (380 cu. ft. at 60°F.) of acetylene plus $2\frac{1}{2}$ molecular volumes of oxygen burns to form 2 molecular volumes of carbon dioxide plus 1 molecular volume of water vapor, liberating 542,700 B.t.u. of heat.

alternating current method of rotating frequency changer sets, which convert the usual frequency to several times that of the supply line.

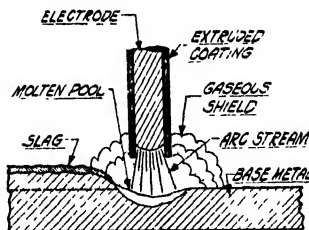
Carbon Arc Welding—In this process the arc is usually drawn between a carbon, or graphite pencil or electrode, and the work. The heat of the arc causes fusion of the base metal and, in case additional metal is required, it also fuses a filler rod which is fed into the joint at the desired rate. This process of welding may be accomplished either by hand or mechanical methods, the latter being commonly called "automatic carbon" arc welding. The hand process is used only on special applications, largely on account of the erratic nature of such an arc. In the automatic process the arc is controlled by superimposed magnetic fields.

Unshielded Carbon Arc Welding is a term applied when either form of carbon arc welding is performed without the aid of appreciable amounts of flux. This process when applied to ferrous materials is used on relatively unimportant joints only, but by proper procedure it is used in the welding of deoxidized copper to considerable extent.

Shielded Carbon Arc Welding comprises the use of fluxes which may be in the form of treated paper, powder, paste or gas, or a combination of these. These fluxes have various functions, among which are: To envelop the molten metal in a noncontaminating atmosphere to the exclusion of the oxygen and nitrogen of the air; to scavenge impurities from the molten metal, to retard the cooling rate of the weld metal, and to produce weld metal of the desired physical properties. This process is applied to most of the important joints to which the carbon arc is suited, generally in automatic form.



Arc welding with bare electrode.



Arc welding with shielded electrode.

Metallic Arc Welding—In this process the arc is struck between a metal electrode and the work. The heat of the arc not only fuses the work but also the electrode, which is in the form of a wire of suitable material. This fused electrode material passes through the arc and unites with the fused base metal to form the welded joint. The process is adaptable to either hand or automatic methods. There are two major classifications of metallic arc welding, *unshielded* and *shielded*. The former term is applied when the electrode is either a bare wire or is lightly coated with small amounts of flux and sometimes called a wash or dust coated electrode.

In shielded metallic arc welding the metallic electrode is covered with a thick layer of fluxing ingredients with or without a fibrous binder. These flux coverings function in several ways to produce weld metal of high physical properties and comparable to the base metal:

1. They usually are consumed more slowly than the metal of the electrode and therefore form a cupped end which constitutes a partial mechanical shield for the arc from the air.
2. Combustion of the fluxes produces an envelope of gases around the arc, which excludes oxygen and nitrogen of the air from contact with the molten metal of the weld.
3. The fluxing ingredients scavenge impurities from the molten metal of the weld.
4. A protective slag covering is formed which covers the top of the weld and protects the molten metal from contamination by oxygen and nitrogen from the air; it also retards the cooling rate and thus partially heat treats the weld.
5. Alloying elements desired in the weld are sometimes supplied in the heavy flux coverings.
6. Materials are sometimes placed in the coatings to increase the arc stability by virtue of their ease of ionization or greater electron emission. Materials may also be added to make the

flow of metal across the arc more uniform by reducing the adhesive force between the molten metal and the end of the electrode or by changing the surface tension of the molten metal so that globular formation is smaller and more uniform.

Shielded arc welding controls the metallurgical processes involved in forming a weld to such an extent that greater amounts of heat are generally used than without shielding. This results in greater welding speeds and at the same time physical properties equal and often superior to those of the base metal.

The average bare electrode deposit has from 0.11-0.15% nitrogen and about 0.3% oxygen (as oxides), while a shielded arc electrode deposit contains from 0.010-0.023% nitrogen and about 0.068% oxygen. A comparison of the physical properties is as follows:

	Bare Electrode	Shielded Arc Electrode
Ultimate tensile strength, psi.....	40,000-60,000	65,000-85,000
Elongation in 2 in., %.....	5-10	20-30
Izod impact, ft.-lb.	5-15	50-80
Fatigue, psi.....	12,000-15,000	28,000-32,000
Specific gravity.....	7.5-7.7	7.82-7.86
Corrosion resistance.....	poor	better than mild steel
X-ray.....	considerable porosity	practically no defects

Atomic Hydrogen Arc Welding—In the atomic hydrogen arc welding process an alternating current arc between two tungsten electrodes in a stream of hydrogen gas furnishes the source of heat. The arc column is defined by a thin brilliant line which forms a loop under the influence of its own magnetic field and the streaming gas. In this arc column, which has a temperature between 6000 and 6500°F. absolute, the hydrogen molecules are completely broken down into atoms, and during this process a great deal of energy is absorbed. When this atomic hydrogen flame, which is coincidental with the arc column, is placed in contact with the metal parts being welded, the dissociated hydrogen atoms recombine into molecules, giving to the surface the heat which was absorbed during dissociation. The weld metal may be supplied as surplus metal from the parts being welded, or be added from a filler rod. The atomic hydrogen arc is surrounded by an envelope of hydrogen gas which protects the work and electrodes from oxidation and reduces existing oxides in the metal. The size of the atomic hydrogen arc may be adjusted by the operator by changing electrode separation during operation; in this way an arc varying in size between $\frac{1}{8}$ in. and over 1 in. is obtainable. The freedom from oxidation, the intense concentration of heat, the flexibility and ease of operation, combined with freedom from magnetic blowing effects, are features which characterize atomic hydrogen arc welding.

Thermit Welding—The thermit fusion process, commonly known as thermit welding, originated with a discovery made in Germany, about 1900, by Dr. Hans Goldschmidt. He found that if a mixture of a metallic oxide and finely divided aluminum were ignited at one spot, the two materials would react exothermically and the reaction would progress throughout the mixture, thereby converting it into two new materials, a superheated mass of the metal itself and a slag composed of molten aluminum oxide (alumina). He further found the reaction would progress so rapidly that in the case of most metals as much as a ton of material could be converted from a cold mixture in half a minute. Later the most suitable kind of iron oxide (Fe_2O_3), the best size of its flakes, and the proper percentage of its fineness for use in welding steel were determined, as well as the possibilities resulting from the addition of such elements as chromium, nickel, vanadium, and manganese to a thermit steel mixture.

In the thermit process the parts to be united are separated by a space, the extent of which depends on their size. The surfaces are thoroughly cleaned by sand blast or otherwise. Usually the space is given the form of a parallel-sided gap cut by means of a gas torch, the slight layer of oxide resulting from the cutting process being apparently beneficial. Around the parts a wax pattern is formed whose shape is that of the reinforcement desired. A sheet iron box is placed around this pattern with a space between it and the pattern, and when the wax has hardened, sand is rammed into the space, provision being made for the proper number of risers and pouring and heating gates. The wax is then melted by directing a flame into each heating gate, and as the wax flows away it leaves clear the space to be occupied later by the thermit steel. Heat is continued so as to dry out the sand mold

and to bring the parts to be united to a red temperature. If multiple sections are to be welded, a two-part mold and a special wooden pattern may be substituted for the box and the wax.

A proper thermit mixture is then placed in a crucible supported over a pouring gate or gates, and when the work is ready it is ignited. In about half a minute the reaction is complete and the thermit steel is then tapped from the bottom of the crucible into the pouring gate. The superheated metal flows around and between the parts to be united, thoroughly combining with their surfaces and welding them into one homogeneous mass, while the molten alumina slag overflows into a basin on top of the mold.

Process Chart for Welding—Table I gives the welding methods that are commonly used and those occasionally used for a number of ferrous and nonferrous metals and alloys.

A. Iron—1. Wrought Iron—The low carbon and high slag content have a marked effect upon the weldability of wrought iron.

Forge Welding—Wrought iron is an ideal material for forge welding.

Resistance Welding—Spot, seam, projection, flash and resistance butt welding may be applied satisfactorily to wrought iron. To produce solid, clean welds and to prolong electrode life all scale, oxide and other foreign matter must be removed from the work.

Thermit Pressure and Fusion Welding—Wrought iron can be successfully welded by either of these processes. If the iron contains heavy layers of slag included, it is sometimes necessary to make two thermit welds to accomplish a satisfactory joint. In the fusion thermit welding process the superheated thermit steel melts the adjacent parent metal to the extent that heavy slag layers may introduce porosity into the thermit weld itself. This occurrence can then be avoided. The collars may be trimmed and the original vee cut through the thermit steel weld, and the gap immediately rewelded. By this method, the new weld fuses only as far as the original weld and almost invariably is sound because the slag of the wrought iron has already been eliminated from this section.

Gas Welding—In oxy-acetylene welding of wrought iron, the slag content sweats to the surface at a comparatively low temperature. This may deceive the inexperienced operator who may regard it as an indication of fusion. Heating must be continued until the base metal itself actually breaks down into a puddle.

This puddle of molten metal must be maintained and the welding rod kept immersed in it to assure fusion and penetration without oxidation. Excessive stirring of the puddle should be avoided as this causes undue exposure and resulting oxidation.

Oxy-acetylene welding rod for wrought iron should either be a low carbon rod or should contain sufficient manganese and silicon so that a weld metal relatively high in these elements will be obtained. The welding flame adjustment should be strictly neutral.

Arc Welding—Arc welding of wrought iron both in flat and vertical positions with coated electrodes is handicapped by accumulations of slag which become trapped in the weld and care must be taken to melt it out. It is customary to melt as little as possible of the wrought iron, and reverse polarity reduces this handicap substantially but not entirely.

The welding of wrought iron with bare electrodes is comparable to welding of low carbon steel. The arcing characteristics of the electrode and the ability to obtain proper fusion between the parent metal and the deposited weld metal are typical of those obtained in welding mild steel.

The strength of welds made with mild steel bare electrodes shows that the weld strength is approximately equal to that of the parent metal, while the weld made with mild steel heavily coated electrodes is greater than that of the parent metal.

Bronze Welding—The bronze welding process is readily applicable to wrought iron.

2. Low Carbon Iron—Iron with a carbon content of 0.06% maximum is one of the most readily welded of the ferrous metals.

When welding low carbon steels preheating is not necessary and subsequent annealing is not required unless it is desired to eliminate the residual stresses set up during the welding operation.

Forge Welding—Low carbon iron is readily welded by the forge welding process.

Resistance Welding—Low carbon irons are readily resistance welded by any of the processes adopted for the welding of wrought iron.

Table I
Process Chart for Welding

Metals and Alloys	Forge	Resist- ance	Thermit Pressure	Gas	Arc	Bronze Weld	Thermit
<i>(See explanation of Code at end of Table)</i>							
A. Iron							
1. Wrought iron	A	A	A	A	A	A	A
2. Low carbon iron	A	A	A	A	A	A	A
B. Carbon steels							
1. Low carbon	A	A	A	A	A	A	A
2. Medium carbon	A	A	A	A	A	A	A
3. High carbon	B	A	A	B	A	A	A
4. Tool steel	B	B	B	B	B	B	B
5. Copper bearing steel	A	A	A	A	A	B	B
C. Cast steel							
1. Plain carbon	B	A	A	A	A	A	A
2. High manganese .....	..	B	B	A-B	A-B	A-B	B
3. Other alloys	B	A	A	A-B	A-B	A-B	A
D. Cast iron							
1. Gray iron .....	..	..	No	A	B	A	B
2. Malleable iron .....	..	..	B	B	B	A	B
3. Alloy cast irons .....	..	..	B	A	B	A	A
E. Low alloy, high tensile steels							
1. Plain nickel .....	..	A	B	A	A	..	B
2. Nickel-copper .....	..	A	B	A	A	..	B
3. Manganese-molybdenum .....	..	A	B	A	A	..	B
4. Carbon-molybdenum .....	..	..	B	A	A	..	B
5. Nickel-chromium .....	..	No	B	A	A	..	B
6. Chromium-molybdenum .....	..	No	B	A	A	..	B
7. Nickel-chromium-molybde- num .....	..	No	B	B	B	..	B
8. Nickel-molybdenum .....	..	No	B	B	B	..	B
9. Chromium .....	..	No	B	A	A	..	B
10. Chromium-vanadium .....	..	No	B	A	A	..	B
11. Manganese .....	..	No	B	A	A	..	B
F. Stainless steels							
1. Chromium .....	..	A	No	B	A	..	No
2. Chromium-nickel .....	..	A	No	A	A	..	No
G. Copper and copper alloys							
1. Copper, tough pitch, elec- trolytic and lake .....	..	..	No	B	A	A	No
2. Deoxidized copper .....	..	B	No	A	B	B	No
3. Commercial bronze, red brass, low brass, ounce metal and hydraulic bronze .....	..	B	No	A	B	B	No
4. Brazing, spring, admiralty, commercial, alpha and yellow brass .....	..	B	No	A	B	..	No
5. Muntz metal, tobin bronze, Naval brass, manganese bronze, extruded brass .....	..	B	No	A	B	..	No
6. Nickel silver .....	..	B	No	A	B	..	No
7. Phosphor bronze, gun metal, bell metal, and bearing bronze .....	..	B	No	A	A	A	No
8. Copper-silicon alloys .....	..	A	No	A	A	A	No
9. Cupro-nickel .....	..	A	No	A	B	..	No
10. Aluminum bronze .....	..	A	No	B	A	..	No
11. Beryllium-copper .....	..	B	No	..	A	..	No
H. Aluminum							
1. High purity aluminum .....	..	A	No	A	A	..	No
2. Commercially pure alu- minum .....	..	A	No	A	A	..	No
3. Al-Mn alloy .....	..	A	No	A	A	..	No
4. Al-Mg-Cr alloy .....	..	A	No	B	A	..	No
5. Al-Mg-Mn .....	..	A	No	B	A	..	No
6. Al-Si-Mg alloys .....	..	A	No	B	A	..	No
7. Al-Cu-Mg-Mn alloys .....	..	B	No	No	B	..	No
8. Aluminum clad .....	..	A	No	No	B	..	No
I. Nickel and nickel alloys							
1. Nickel (99%) .....	..	A	No	A	A	A	No
2. 67% Ni-30% Cu .....	..	A	No	A	A	A	No
3. 79% Ni-13% Cr-6% Fe .....	..	A	No	A	A	..	No
4. 66% Ni-29% Cu-2.75% Al .....	..	A	No	A	A	..	No
J. Lead .....	..	..	No	A	No	..	No
K. Magnesium alloys .....	..	A	No	A	No	..	No

Code: A—Commonly used. B—Occasionally used under favorable conditions. No—Not used.
(..)—No information available.

Gas Welding—This process is applied similarly to that in the case of low carbon steels except that the filler rod utilized is of low carbon iron which is necessary in order to retain the corrosion resisting properties of the parent metal and to obtain a weld of similar characteristics.

Arc Welding—Arc welding of low carbon iron is accomplished with the use of mild steel, heavy coated electrodes. The welding current and procedures are the same as for welding mild steel. Bare electrodes can be used with a resulting decrease in the corrosion resisting properties of the weld and adjacent parent metal. Iron with carbon content below 0.15% absorbs gas readily from the atmosphere during the welding. For the highest quality weld, complete shielding is necessary.

Bronze Welding—Low carbon iron may be bronze welded quite readily by either the arc or gas process. This does not require the heating of the steel to as high a temperature as is necessary for fusion welding, which is a decided advantage.

Thermit Welding—Iron with a carbon content of 0.06% and less can be successfully welded both by the thermit fusion and pressure processes.

B. Carbon Steels—1. Low Carbon Steel (Up to 0.30% Carbon)—These steels are easily welded by all the welding processes and the resultant welds and joints are of extremely high quality.

Gas Welding—The joint edges should be clean and properly prepared to facilitate good fusion and a sound weld. When welding long seams, allowance must be made for the effect of heat along the line of weld which causes contraction during cooling and tends to pull the unwelded ends of the plates together. The normal spacing that is allowed in welding is $\frac{1}{4}$ in. opening per ft. of seam. Faster welding speeds will materially reduce the amount of contraction obtained. When making fillet welds the overlapping plates should be held close together.

A neutral flame is frequently used when welding steel of this class. Increased welding speeds are possible, however, by using a slightly reducing flame. This type of flame carburizes the kerf surfaces, thereby lowering their melting temperature and making possible fusion of the deposited metal to the plates at a temperature lower than would normally be required. Welded joints made in this way are of high quality and the fusion zone is not hard or brittle.

The preference for filler metal at the present time is for the so-called high test welding rods with about 0.15-0.20% carbon and certain metallic elements that will insure freedom from included oxides and give the proper fluidity in the molten metal.

Arc Welding—Low carbon steels are readily welded by all forms of this process. Many types of electrodes may be used such as bare, dust coated, washed or dipped, shielded arc, or flux coated. Carbon arc welding is also practical on these steels and the results obtained are a function of the technique employed.

When welding long seams the progressive shrinkage of the deposited metal tends to pull the plates together. This is less severe than with gas welding and an allowance of $\frac{1}{4}$ in. per ft. is sufficient to take care of this condition. Proper clamping and tacking and the adoption of special welding procedures such as the step back and skip procedures are commonly used to prevent distortion and residual stresses. The design of the structure, preparation of joint, size of electrode used, the welding current and voltage are of extreme importance.

Carbon arc welding varies from metallic arc welding in that the arc is drawn between the base metal and a carbon or graphite electrode. The arc heat in this case is used only to melt or fuse the base metal and the addition of filler metal when required must be obtained by a specially prepared flange or upset edge at the joint or from some extraneous source. The latter method of adding filler metal can be accomplished by placing additional metal on the seam to be welded or by feeding it into the weld in a manner similar to that employed by the oxy-acetylene process.

Carbon arc welding done without the presence of a flux or shielding atmosphere may result in brittle welds. Shielding the arc by painting the weld with a special flux or by introducing a suitable fluxing material into the arc produces welds of high quality.

Bronze Welding—Low carbon steels may be bronze welded quite readily. The joint surfaces are "tinned" through the use of a suitable flux and bronze welding rod. The bronze is then melted into the space between the tinned surfaces to be joined. This work is ordinarily done as a continuously progressive operation, the tinning being carried out for a distance and then additional bronze being deposited before the section becomes cold. With recently developed bronze rods, strengths of welds of the order of 55,000 psi. can be obtained. This process does not require the

heating of the steel to as high a temperature as is called for by fusion welding which is often a decided advantage.

Thermit Welding—Fusion thermit welding is successfully carried out on low carbon steels by using forging thermit. The welds give tensile strengths of 70,000-75,000 psi., elongations of 15-20% in 2 in., and good impact values. Before welding the joint surfaces are preheated to 1600-1700°F. The purity of the weld deposit eliminates the need of subsequent forging or heat treatment in order to develop satisfactory physical properties.

2. Medium Carbon Steel (0.30-0.50% Carbon)—Steels in this class can be welded with the various fusion processes. The technique and materials used are dictated by the metallurgical characteristics of the base metal. In some cases preheating and subsequent heat treatment may be required to produce the desired weld quality. This condition is especially true for steels containing over 0.40% carbon.

Gas Welding—In welding this material better welds can be obtained if an excess of acetylene is used in the welding flame. The recommended welding procedure is similar to that for low carbon steels. As a rule little trouble is experienced from the formation of hard and brittle constituents as a result of rapid cooling. The quality of the finished joint will be improved if it is heat treated after welding.

Arc Welding—The weldability of steels of this grade depends upon the carbon content of the base metal because the rapid cooling may produce a martensitic or troostitic structure. The formation of martensitic or troostitic structures in the fusion zones tends to make these areas hard and brittle and of an undesirable condition.

Preheating temperatures of 300-500°F. have been found effective in eliminating and reducing the formation of hard and brittle areas. By heating to 1100-1200°F. it is possible to restore the desired properties in the areas affected by the welding heat.

Shielded arc electrodes of the type used on low carbon steels are satisfactory for the welding of steels in this class.

Thermit Welding is carried out as successfully on these steels as on the lower carbon grades. Forging thermit is generally used but the increase in carbon from the parent metal produces a somewhat higher tensile strength and lower ductility than is the case when welding the lower carbon steels.

3. High Carbon Steels (0.50-0.90% Carbon)—Because of the higher carbon content, steels of this type are more difficult to weld.

Gas Welding—As these steels are often heat treated the welding heat will affect such treatment and produce a joint of different properties than those possessed by the original metal. Care should be taken to prevent overheating of the parts and the weld should be completed as quickly as possible. These materials melt at a lower temperature than the lower carbon steels and tend to spark when overheated, a condition which aids from overheating the parts.

A carburizing or excess acetylene flame is advantageous in securing strong sound welds. High carbon filler rods are often used although satisfactory results can be obtained with medium carbon filler metal, which produces a weld of moderate strength but the increase in ductility is often beneficial. By heat treating after welding it is possible to eliminate the effect of the welding heat and to improve the strength of the weld.

Arc Welding—Steels in this group do not give good properties after arc welding. Hardness and brittleness may be obtained in the fusion zone. For the best results, it is recommended that the parts be preheated to at least 500°F. before welding and subsequently heated to 1200-1450°F.

Welding on these steels is often done to rebuild a worn surface or to develop a hard wear resistant surface. In such cases unless the carbon content of the parent metal approaches the upper limit, preheating or subsequent heat treatment are not necessary.

Mild steel electrodes of the shielded arc type can be used to make joints on these steels. The deposited metal tends to absorb carbon from the base metal so loses considerable ductility. Austenitic electrodes are often recommended and the resultant welds have good physical properties but the fusion zone may still be hard and brittle.

Thermit Welding—These steels are readily welded by the fusion thermit process. Slightly lower preheating temperatures are used than is the case with the lower carbon steels because of the lower melting temperatures of the parent metal.

If forging thermit is used the pick up of carbon will be sufficient to produce a

weld strength of 90,000-100,000 psi. In many cases, however, hardness or wearing qualities are of prime importance and special thermit is required.

The preheating and inherent characteristics of the thermit process eliminate the rapid cooling obtained in arc and gas welding, consequently subsequent heat treatment of joints even on these high carbon steels is not required for satisfactory physical properties.

4. Tool Steels (0.80-1.50% Carbon)—These steels are relatively difficult to weld.

Gas Welding—Drill rods, available in the various diameters required for welding and of carbon content sufficiently high to cover the carbon range are generally used in welding these steels. The use of a carburizing or excess acetylene flame adjustment is advantageous in securing sound strong welds. Flux suitable for cast iron welding should be used sparingly. Preheating and annealing are usually necessary.

Arc Welding—Because of the heat effects of arc welding it is seldom used for steels of this type. If welding is required, one of the following procedures is recommended:

(1) After annealing, preheat the parts and weld with a suitable shielded arc electrode followed by heat treatment to restore the desired properties. (2) Preheat the parts and use an austenitic electrode. Preheating will aid in preventing the formation of a hard fusion zone and the weld will not be hard because of its austenitic condition. (3) Preheat the parts and deposit one or more layers on the kerf surfaces of the parts with a shielded arc electrode. These layers dilute the carbon so that the parts can then be more readily welded together. It should be noted that this process does not produce a high carbon weld.

Thermit Welding—Fusion thermit welding is not commonly used on these steels, but successful joints have been made on materials with carbon contents of 1.10%. Forging thermit can be used but the tensile strength will not be equivalent to that of the parent metal. Higher carbon thermit can be used if the strength is of prime importance. Heat treating the weld and fusion zone after welding is recommended in order to produce the best properties.

5. Copper Bearing Steels—These steels are generally of the low carbon variety and contain from 0.20-0.30% copper. The same welding processes are applicable as for ordinary steels of the same carbon range. Welded joints made by the gas or shielded arc processes are in general as resistant to corrosion as the copper bearing steels.

C. Cast Steel—Welding of low carbon steel castings presents no particular difficulties if the casting is properly prepared, is reasonably clean and the ordinary precautions are taken to avoid setting up excessive expansion and contraction stresses in the metal. With carbon content of the casting above 0.25% and with special alloy compositions, certain precautions are necessary in applying welding.

1. Plain Carbon Steel Castings—Before welding steel castings an effort should be made to learn the analysis in order to weld successfully the high carbon and the alloy castings. Castings under this heading should not exceed 0.25% carbon and a negligible amount of alloying materials. Castings of such analyses present no difficulties in welding and can be handled approximately the same as for low carbon rolled steel.

Gas Welding—It is customary to use a general purpose filler rod for welding these castings although for the best results the analysis of the filler metal should be similar to that of the base metal.

Arc Welding—The procedure for electric arc welding steel castings (low and medium carbon) is essentially the same as for rolled steel of similar analysis. For the best results a high grade heavily coated electrode is considered desirable. The surfaces to be welded should be carefully cleaned of sand inclusions, cracks, porosity and dirt. Multilayer welding and high currents should be employed if the carbon content is low, but small diameter electrodes and low currents are necessary when the carbon content is high, while in some cases preheating and slower cooling are desirable.

Bronze Welding—Bronze welding is satisfactorily applied to steel castings, especially where the difference in surface appearance of the casting is not objectionable. Both gas and electric arc processes are used, the only preparation necessary being that involved in preparing and cleaning the surfaces to be welded as described above under Low Carbon Steels.

Thermit Welding—Repairs are readily made and heavy cast steel parts are commonly reclaimed by the thermit process. Where the work consists of applications such as replacing teeth in large gears or pinions, the fact that the tooth is a com-

paratively small projection on an extremely heavy casting must be taken into account. If the casting were preheated at the weld only, the heat would be carried away into the casting so rapidly that fusion between the weld metal and the parent metal could not be obtained. It is therefore necessary to preheat the entire casting. Forging thermit may be used for this work, although where parts are subject to abrasion and wear, "wabblers" thermit, providing a hard wear resistant machinable steel, may be employed.

2. High Manganese Steel Castings—Welding these castings is mostly for the purpose of restoring portions worn away or for the repair of cracked and broken pieces. The manganese content is frequently as high as 12% or more, and the carbon content ranges from 1-1.40%.

Resistance Welding—Electric resistance welding of manganese steel parts has not been used to any great extent because of the difficulties that have been encountered in obtaining strong welds by this method. It is possible, however, that resistance welding can be successfully used by proper adjustment of current and time of application.

Gas Welding—In welding these castings a shallow zone must be heated to a temperature close to 2200°F. and the filler metal then applied. The use of a rod of the same manganese content as the casting should be used, and if in addition the rod contains from 3-5% nickel its use will produce reliable welds. The high nickel content tends to inhibit embrittlement under slow cooling so that no quench is necessary.

Arc Welding—In arc welding high manganese steel (12-14% Mn and not over 1.25% C), a shielded electrode of a type to give properties in the deposited metal approximately the same as the base metal should be used. The weld should be in an austenitic condition even after slow cooling, and the welded part should not be quenched because of the danger of cracking. The weld deposit is in such cases rather soft but upon cold working will produce a hardness of 45-50 Rockwell C.

Thermit Welding—Thermit welding of manganese steel is not generally practiced because of the effect upon the adjacent steel of the heat of the weld. A fairly successful weld can be made if the whole mass can be preheated and then heat treated after welding, but this is not always possible.

3. Alloy Steel Castings—Alloy steel castings are in general welded by the same process as is used for rolled alloy steel of the same composition. The number and character of the alloying elements have a decided effect on the welding properties of the castings.

Resistance Welding—Electric resistance welding has not been applied to any extent to alloy steel castings because of the varying forms and contours of the castings commonly encountered. It is possible, however, that resistance welding can be applied if the work is held in suitable jigs and there is proper adjustment of current and time of application.

Gas Welding—It is customary to modify the filler rod from the type used in welding carbon steel castings so that the weld deposit will be similar to that of the alloy casting. The same requirements for fluidity of deposit are necessary as in the case of carbon steel castings, in order that impurities may be brought to the surface in the melting operation.

Arc Welding—The procedure for electric arc welding of alloy steel castings is quite similar to that used on carbon steel castings, the only modification being in the coating of the electrode which should be so proportioned as to influence the weld metal deposit. It is customary to use heavily coated electrodes for this purpose and the surfaces to be welded should be thoroughly cleaned before welding. In some cases preheating is considered desirable, and in practically all cases a heat treatment after the welding is completed is desirable.

Thermit Welding—With the thermit weld metal, it is possible to match the composition of the casting by the addition of metallic elements to the thermit mixture.

D. Cast Iron—**1. Gray Iron**—In welding gray cast iron, preheating is usually necessary to avoid stresses. Gray iron castings may be welded hot and then allowed to cool slowly so as to maintain their characteristic gray iron structure. Only in certain cases where the structure of the weld metal is of little importance can preheating be avoided.

Forge Welding—Gray cast iron cannot be forge welded.

Gas Welding—Gray iron castings should be preheated to a low red heat and welded while hot with a cast iron welding rod containing a high percentage of

silicon. A suitable flux should be used to remove oxides. When the weld is completed, the whole casting should be allowed to cool slowly to room temperature. With this procedure the weld will be strong, yet soft and machinable.

Arc Welding—Preheating the casting to a dull red heat accelerates the welding, relieves strain and reduces the tendency toward unmachinable spots and cracks, and helps to retain the characteristic gray iron structure. Excessive strain or breakage may be encountered in welding gray cast iron which may be intensified by a hard area, containing carbides of iron, outside the weld. For this reason castings lighter than $\frac{1}{4}$ in. are seldom welded. It is desirable that the casting be annealed after welding.

Special electrodes, either coated or uncoated, which give a good bond with the casting are used. A rather low current should be used, and the welding done intermittently. Each bead should be slightly peened and allowed to cool slightly before depositing the next bead. All of these considerations tend to reduce the hardening effect along the line of fusion. Where machinability is of primary importance and strength is of secondary importance, nonferrous electrodes such as high nickel (67%) are available. These electrodes produce a soft, machinable deposit without any tendency to harden at the fusion line. This deposit is also advantageous where appearance is important, since the color matches that of the cast iron.

Bronze Welding—When gray iron castings are bronze welded, comparatively little preheating is necessary. When the base metal is raised to a temperature of 1500-1600°F. the bronze will "tin" the cast iron surface, and make a bond as strong as, or stronger, than the cast iron.

When bronze welding with the arc, preheating is generally unnecessary, but it should be kept in mind that too much current is detrimental to satisfactory welding and the currents used should be as low as possible consistent with the size electrode and part being welded.

Thermit Welding—The thermit process, while entirely suitable for welding gray iron, cannot be used on all castings because of the difficulty of allowing properly for shrinkage of the weld metal when it cools. Contraction of thermit steel is approximately double that of cast iron so that, generally, if the length of the crack to be welded is more than eight times the thickness of the section, the difference in shrinkage along the line of fracture will result in small hairline cracks in the weld.

2. **Malleable Iron**—Fusion welding of malleable castings is generally regarded as unsatisfactory (even when the castings are remalleableized afterward). For this reason repairs to malleable castings are generally made by bronze welding. Malleable iron foundries frequently reclaim defective castings by fusion welding the white iron castings before malleableizing.

Gas Welding—For the oxy-acetylene welding of defective white iron castings before malleableizing, white iron welding rods of the same approximate analysis are used. The salvaged castings are then put through the malleableizing process.

Arc Welding—Malleable iron castings can be welded with the arc process using low heat. In general, these castings should be treated the same as gray cast iron, using the same precautions and procedure. After welding, the casting should be put through the same annealing process by which it was originally made. Annealing is helpful if full heat treatment cannot be given.

Bronze Welding—The temperature of 1500°F. required in the base metal for bronze welding is not so high as to affect seriously the properties of malleable iron, so effective repairs can be made by this process. Either the gas or arc may be used.

3. **Alloy Cast Irons**—The welding procedures for most alloy cast irons are essentially the same as for gray iron. Filler material should be of the same alloy content as the base metal, or if such material is not available the welds should be made with high quality gray iron rod. For arc welding, see under "Cast Iron."

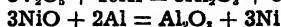
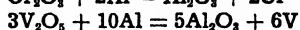
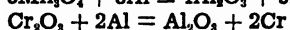
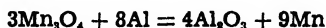
E. Low Alloy, High Tensile Steels—The low alloy, high tensile steels are readily welded by the various welding processes. The amount of alloying element in these steels is only slightly greater than in ordinary mild steels and is considerably less than in many alloy steels. These steels have higher physical properties than carbon steels and usually possess higher resistance to atmospheric corrosion. When welding these steels by a process wherein metal is added, the metal need not necessarily have the same composition (provided it has the same physical properties), unless resistance to corrosion is a factor, in which case the weld metal should be of a composition similar to the base metal. Heat treatment is desirable for the various alloys, to develop the required physical properties.

Gas Welding—Where the strength is of importance, a welding rod of the high

test steel type will give satisfactory results in oxy-acetylene welding. Where corrosion resistance is a factor, the welding rod should be of the same composition as the base metal.

Arc Welding—When arc welding these materials, a shielded arc type of special electrode is generally used.

Thermit Welding—Through the addition of metallic elements to the thermit mixture, either by means of metallic pieces, which are melted during the reaction, or in the form of combinations of oxides of the required elements with aluminum, a wide variation in the analysis of thermit steel is made available so that it is entirely possible to match the analyses of a number of low alloy steels. The following are chemical formulae of the aluminum reduction of several oxides used for this purpose:



Since these steels are used mainly for developing strength, ductility, resistance to shock and resiliency, it is usually desirable to heat treat the welds made in these steels. The heat treatments recommended for these alloys are given below.

1. **Plain Nickel Alloy Steel**—While the 3-3½% nickel alloy steels do not necessarily need heat treatment if the carbon content does not exceed 0.25%, such alloy steels with carbon contents over 0.25% require a preheat of from 300-600°F. Steels in this class have a tendency toward air hardening and they require slow cooling in order to retain the desired physical properties.

2. **Nickel-Copper Alloy Steels**—The alloy steels in this class contain from 1-2% nickel and 1-1.6% copper, while the carbon content is usually limited to 0.25% as a maximum. No preheat is required for the ordinary welding of these alloys except when the carbon content exceeds 0.20% when in some cases it is considered desirable. In such cases a preheat of from 250-300°F. will enable the desired physical properties to be obtained.

3. **Manganese-Molybdenum Alloy Steels**—The steels in this class are alloyed with from 0.60-1.60% manganese and 0.30-0.70% molybdenum, and the carbon is usually kept below 0.25% as a maximum. These steels do not ordinarily require preheating except in certain cases where the carbon content approaches the upper end of the range. In such cases and for heavy or difficult sections, the preheating at 250-300°F. is an advantage.

4. **Carbon-Molybdenum Alloy Steels**—This class of steel is similar in many respects to the manganese-molybdenum alloys except that the manganese is held down to a normal range of from 0.30-0.60%; the molybdenum content is a little high, ranging from 0.30-1% and the carbon content is held down to the same top limit of 0.25%. Here, also, preheating is not required under ordinary conditions, although when the molybdenum approaches the upper end of the range, (above 0.50%) a preheat of 350°F. is considered desirable for best results in welding. A similar preheat is also considered desirable if the carbon content approaches or exceeds the limit of 0.25%.

5. **Nickel-Chromium Alloy Steels**—This classification embraces several analyses in which the nickel content ranges from 1% on the low side to 3½% on the high side, while the chromium ranges from 0.40% as a minimum to 1.75% as a maximum; the carbon content varies from a maximum of 0.20% for the lower tensile ranges to 0.55% for the higher tensile ranges. These steels are not capable of being safely welded without preheating. For the lower tensile ranges having a maximum of 0.20% carbon a preheat of from 200-300°F. is all that is necessary, but with the higher carbon contents that accompany the increased percentages of nickel and chromium a 600-800°F. preheat is considered desirable, followed by slow cooling. For the highest carbon, nickel, and chromium contents it is even desirable to raise the preheat temperature to 900-1100°F.

6. **Chromium-Molybdenum Alloy Steels**—These steels are similar in many respects to the preceding class. There is a much used series of alloys in this classification with the carbon range of 0.25-0.55%; molybdenum 0.15-0.25%; and the chromium 0.50-1.10%. These steels were designed especially for high temperature service and with these high chromium contents require a considerable degree of

preheat, ranging from 300-800°F., and slow cooling is desirable after the welding operation.

7. Nickel-Chromium-Molybdenum Alloy Steel—This steel contains 1½-2% nickel, 0.20-0.40% molybdenum, and 0.30-0.90% chromium. While it is an alloy that is in extensive use, it has not been welded to a sufficient extent to warrant a statement.

8. Nickel-Molybdenum Alloy Steels—In these steels the carbon content is kept low; the nickel range is 1.65-3.75%, and molybdenum from 0.20-0.30%. Welded applications have not been sufficiently frequent to furnish the desired data.

9. Chromium Alloy Steel—This steel is used in two ranges of carbon, one up to 0.25% as a max. and the other from 0.35-0.55%. With the former the chromium range is 0.60-0.90%, whereas with the latter it is 0.80-1.10%. Preheating is essential before welding. The temperature range recommended is 200-800°F.

10. Chromium-Vanadium Alloy Steel—This steel has two carbon ranges, one up to 0.25% max. and the other 0.25-0.55%. In both cases, however, the chromium is 0.80-1.10% and the vanadium 0.15-0.20%. These steels all require preheating in order to obtain satisfactory results in welding. The preheating range is 200-800°F. With this alloy sample welds may be required in order to ascertain the properties that can be obtained from the welding operation and particularly the effect of the heat-treating operation.

11. Manganese Alloy Steels—The manganese in these steels is 1.6-1.9%, carbon 0.25-0.55%. For satisfactory welding of these steels preheating is essential, the desired range being from 400-800°F.

F. Stainless Steels—The stainless alloys may be grouped into two classifications for welding considerations: (1) Stainless irons which contain from 3-28% chromium, with or without traces of nickel, and which are essentially magnetic and ferritic in character, and (2) stainless steels which contain chromium and nickel, with or without smaller amounts of molybdenum, manganese, columbium, silicon, or titanium, all of which are in such proportions as to result in an essentially austenitic phase.

1. Chromium Alloys—The alloys that come within this classification contain from 12-28% chromium as the essential alloy constituent, and are termed stainless irons. These alloys show a tendency toward grain growth in and near the weld. This tendency toward coarsening of the grain increases markedly with the chromium content and frequently results in undesirable brittleness in the welded equipment made from the higher ranges of chromium content. Small additions of nitrogen alleviate this tendency toward grain growth.

Probably the most widely used compositions for fabricated equipment come within the range of 15-18% chromium with 0.10% max. carbon. This material is readily welded and when the fabricated equipment is properly heat treated (1450°F., slowly cooled) it possesses a satisfactory combination of physical properties in both weld and plate and sufficient corrosion resistance to meet the needs of the majority of applications.

Gas Welding—Chromium irons may be welded by the oxy-acetylene method provided adequate precautions are taken, best results being obtained with a practically neutral flame. A slightly reducing flame will result in brittleness of the weld area caused by carbide formation due to affinity of chromium for carbon. A slightly oxidizing flame will result in the formation of chromium oxides, which, being refractory, sometimes results in insufficient penetration of the heat causing reduced weld strength and slag inclusions.

Arc Welding—Electric arc methods, mainly the metallic arc, are successfully used in welding stainless irons. A coated wire electrode with the metal wire of composition similar to the plate metals, with preferably slightly higher chromium, in order to provide for the metal loss during welding, is recommended.

2. Chromium-Nickel Alloys—Alloys in this classification contain sufficient nickel and manganese in addition to the chromium, with or without small amounts of other metals, to maintain an essentially austenitic condition. The composition, which probably represents the major tonnage of plates and sheets fabricated into equipment by welding, is 18% chromium, 8% nickel, and 0.10% carbon max. These chromium-nickel steels are also furnished commercially in ratios of 25-12 and 25-20, all of which have been successfully welded by methods described below.

All stainless steels, except those stabilized by columbium or titanium, when exposed to temperatures of 700-1500°F. will show an accumulation of carbides at the grain boundaries. This is known as carbide precipitation and is found in stain-

less steel that has been held in this temperature range. It is found also in lines approximately parallel to the weld bead and perhaps a quarter inch distant even in stainless plates that had been properly heat treated before welding. This is the result of the heat of the welding operation and is evidence that the plate metal in that narrow zone had been heated to a temperature range wherein carbide precipitation can take place.

This accumulation of carbides at the grain boundaries in the narrow zones adjacent to the welded bead will, in the majority of cases, show less resistance to many corrosive media than will the metal at some distance from the weld and where it had not been held in this susceptible temperature range. It is coming to be standard practice, therefore, in fabricating stainless steel vessels by welding to heat treat the equipment after completing the welding in all cases except those in which columbium or titanium is present as a stabilizing element. The heat treatment commonly used is to heat to approximately 1950°F. and quench in water. In addition to the heat treatment increasing the overall corrosion resistance of these alloys, it also puts the metal in its softest, most ductile and impact resistant form.

Gas Welding—This method is generally applied to the lighter gages. On the thinner sections, a flange type weld is used and the edges joined without the addition of welding rod. On gages where metal must be added, a bare (uncoated) rod is used with a flux added as a thin paste to the work.

The wider distribution of heat from the acetylene flame, as contrasted with the intense and local effect of the arc methods, make it desirable to use chill blocks when welding with the gas. Likewise, as a result of the more general heating and expansion of the metal sheet, since stainless steel has a 50% higher coefficient of expansion than carbon steel, it will be found convenient to use jigs and clamps to hold the work.

It is of paramount importance in gas welding stainless steel to adjust the flame so that it is practically neutral. This will avoid excessive carbon pick up in the metal which would materially reduce the corrosion resistance of the resultant weld.

Arc Welding—The usual methods of arc welding are successfully applied to joining the stainless steels. Altogether satisfactory electric welding is done using direct current in preference to alternating current. Reversed polarity, that is, work negative and electrode positive, is normally used. Coated metallic electrodes are preferred. The composition of the welding wire should be similar to the composition of the plate, preferably with the chromium in the wire slightly higher.

As pointed out previously, austenitic steels are susceptible to grain growth at high temperature. Overheating is, therefore, to be avoided. Adjust the current quality to give smooth arc and proceed with laying down the bead as rapidly as is consistent with good welding practice.

G. Copper and Copper Alloys—1. Copper, Tough Pitch, Electrolytic and Lake—The materials of this group have high thermal conductivity and a tendency toward oxide embrittlement which are the chief obstacles to welding them. The high thermal conductivity requires an unusually high input of heat in the welding zone in order to compensate for the loss of heat to the surrounding metal. The cuprous oxide in the base metal adjacent to the weld is reduced by the hot hydrogen gas or tends to collect at the grain boundaries causing a material reduction in weld strength which may, however, be corrected by hot forging.

Resistance Welding—The resistance welding of this material has been unsuccessful commercially on account of its high thermal and electrical conductivity. Resistance brazing is possible by use of carbon resistor electrodes. Resistance flash butt welds are commercially possible on copper wire and rods with a special procedure.

Gas Welding—These materials can be gas welded with a sufficiently large flame or by preheating with a charcoal fire or with some form of preheating torch. The work should be insulated for heat conservation as well as for comfort of the welding operator. The back hand method of welding is preferable for thicknesses greater than $\frac{1}{4}$ in. If the full strength of the annealed metal is desired, it is necessary to hot forge the weld or cold peen and anneal it.

Arc Welding—These materials can be readily welded by the carbon arc, using a phosphor bronze or silicon-copper filler rod. The metallic arc is sometimes used for sheets $\frac{1}{8}$ - $\frac{1}{2}$ in. in thickness, but is unsatisfactory for thicker sheets. It is generally necessary to do flat welding though under certain conditions some position welding can be done with the carbon arc and a silicon-copper filler rod.

2. Deoxidized Copper—This material is a decidedly easier metal to weld than is the oxygen-bearing copper and it should be used in all cases where the equipment

to be welded is to be subjected to severe service. It is not subject to hydrogen embrittlement and, though its thermal conductivity is somewhat lower than that of tough pitch copper, this property is still high enough to call for a high input of welding heat.

Resistance Welding—This material is nearly as difficult to resistance spot and seam weld as the preceding material. Where necessary to resistance spot and seam weld, a satisfactory connection can be made by inserting thin phosphor bronze strips or coating the surfaces with tin or solder.

Gas Welding—The procedure for gas welding of this material is much the same as that for the materials of the preceding group. Hot forging of the weld or cold hammering followed by an anneal will improve the ductility and strength, but the material is generally used in the as-welded condition.

Arc Welding—The procedure for arc welding of this material is quite similar to that for the materials of the preceding group, but it is difficult to weld this material in thicknesses greater than $\frac{1}{4}$ in. by the metallic arc process. With the carbon arc process satisfactory results can be obtained.

Bronze Welding—Bronze welding of this material has proven particularly satisfactory in connection with copper tube and brass pipe plumbing installations.

3. Commercial Bronze, Red Brass, Low Brass, Ounce Metal, and Hydraulic Bronze—These constitute some of the most common commercial alloys of copper and are usually encountered in the form of sheets, tubes and wire. The leaded alloys are largely used as castings for pipe fittings, or valve bodies. The group is, in general, quite weldable except that, if the weld metal is superheated, trouble is experienced with zinc vaporization. The unstable lead oxides sometimes weaken the welds made in the leaded alloys.

Resistance Welding—Resistance, spot and seam welding of this group of materials is almost as difficult as on copper, because in addition to the high electrical and thermal conductivity there is danger of zinc vaporization.

Gas Welding—The procedure for this class of material is similar to that for the two preceding groups. Where for artistic purposes an exact color match is desired it is usually necessary to use strips of the base metal for filler metal. A strongly oxidizing flame is sometimes used to suppress zinc vaporization. A good brazing flux is always required.

Arc Welding—The arc welding of materials in this group is difficult except where the carbon arc can be played on a zinc-free filler metal as applied in flat butt or lap welding so that the base metal is not fused but is heated by the highly superheated weld metal. This is the only manner in which serious difficulty from zinc vaporization can be avoided.

Bronze Welding—This material can be readily bronze welded provided a satisfactory flux is used.

4. Brazing, Spring, Admiralty, Commercial, Alpha, and Yellow Brass—These more common of the brass alloys have a sufficiently low melting range and heat conductivity to render oxy-acetylene and resistance welding comparatively easy. They are not, however, as easy to weld by the electric arc method as the materials in the preceding group and the use of metallic arc welding is not recommended for any application on account of the vaporization of the zinc. A brazing flux is used invariably on this group of alloys.

Resistance Welding—Resistance welding can be applied to this group of materials by machines that have carefully controlled pressures and current timing. The material must be carefully cleaned and prepared as any unexpected change in conditions may cause burning of the work or of the electrode.

Gas Welding—While the gas welding process is considered the most satisfactory method for welding these alloys, the temperature of the gas flame is high enough to render rapid vaporization of the zinc unless care is taken to avoid it by either controlling the heat of the flame in the application or by using a strongly oxidizing flame. Special fluxes are also used for the purpose of covering the molten weld metal with a suitable film to suppress zinc vaporization and obtain sound weld metal.

Arc Welding—While metallic arc welding is generally unsatisfactory for this group of alloys, it is possible to apply carbon arc welding by a suitable technique in which the arc is directed toward the zinc-free filler metal rods.

5. Muntz Metal, Tobin Bronze, Naval Brass, Manganese Bronze, and Extruded Brass—The materials in this group are similar in welding properties to the yellow brass group. They have good hot forging and extruding qualities and also have high strength and good corrosion resistance.

Resistance Welding—This material can be resistance, spot and seam welded quite satisfactorily. The current values are about the same as those required for steel. The pressure exerted on the work should be light and the balance of application of heat should be as short as possible.

Gas Welding—Oxy-acetylene welds in this material are strictly fusion welds, although the heat conductivity of the material is still high as compared with that of steel, so that a large flame is necessary. Zinc vaporization is suppressed by using an oxidizing flame. Where used in the form of architectural bronze a good color match is obtainable in welding if filler metal strips are cut from the base metal.

Arc Welding—These materials are not commonly welded by the metallic arc process, but welds are possible by use of the carbon arc method using a long arc. They are not ordinarily welded in thicknesses exceeding $\frac{1}{8}$ in.

6. Nickel Silver—This group of materials is used where a white metal or artistic metal is desired and to some extent for reason of corrosion resistance. The nickel content renders the material easier to weld on account of the lower thermal and electrical conductivity. There is a tendency for nickel oxide to form but this can be checked to some extent by the use of a suitable flux.

Gas Welding—The oxy-acetylene process is well adapted for the welding of this material, particularly in connection with certain lapped connections. Nickel silver welding rod is given the preference because it makes a good color match with this material. This material is largely used in architectural designs and is particularly well adapted for butt or mitered joints. One of the essentials for applying gas welding to this material is that both the base metal and the welding rod must be cleaned and covered with a good brazing flux, and a neutral flame should be used.

Arc Welding—Carbon arc welds can be made satisfactorily if phosphor bronze electrodes are used, although silicon-copper electrodes should be used where it is necessary to perform position welding. In case of metallic arc welding covered electrodes are necessary to obtain satisfactory strength and color match. With this process difficulty is experienced with vaporization of zinc from the base metal.

7. Phosphor Bronze—Most of these alloys have insufficient phosphorus to insure thorough deoxidation and as a result tin oxide and in some cases lead oxide are likely to be developed in the weld metal. This should be avoided by keeping the heat, in the case of arc welding, off the base metal and playing it on the weld metal which should have sufficient phosphorus to insure deoxidation. The metal is inclined to be hot short and subject to dendritic shrinkage cracks under certain conditions. For instance, a wide spreading heat and slow cooling are likely to produce these hot short cracks and porous places in the weld metal. A narrow heat zone with quick solidification promotes soundness.

Resistance Welding—This process of welding is applicable only to this group of metals in sheet and wire free from lead. It welds at a lower heat and at about the same pressure as brass, and strong sound welds are the usual result.

Gas Welding—On account of slow cooling and high shrinkage this process of welding is not so desirable as some of the others. Welds of this process must necessarily be fusion welds if phosphor bronze welding rods are used, but the base metal need not be fused if the rods are of yellow bronze. The latter do not give a good color match but this yellow bronze is the easiest metal to apply without danger of developing hot short cracks. With either metal a neutral flame and a good brazing flux are desirable. If a phosphor bronze rod or cast bronze rod with a high percentage of tin is to be used, a reasonable degree of preheat is necessary.

Arc Welding—Arc welding is satisfactorily applied to this group of materials. With the carbon arc process, the arc should be played on the weld metal so as to avoid oxidation of the tin in the base metal. With this process the concentrated application of heat tends to keep the contraction at a minimum. The use of a flux is desirable although not entirely necessary. Welds of this type can be made only in the flat or nearly flat position. If the metallic arc process is to be used a flux coated phosphor bronze electrode is to be preferred to the bare electrode in order to reduce the tendency toward oxidation of the tin.

8. Copper-Silicon Alloys—These copper-silicon alloys, although commonly carrying about 96% of copper, have low heat conductivity and develop a continuous protective film on the metal the instant it is melted. This film helps to hold the metal in place in fusion welding. Rapid solidification and cooling are desirable in order to keep the grain size small. Considerable care must be taken in the welding of this material to insure a fine grain structure which results in suitable tensile

strength and ductility. The work for welding this material is usually set up in jigs so as to hold the edges rigid. The welds in these alloys are improved in both tensile strength and ductility by peening and annealing, the peening to be done when the metal is cold or nearly cold.

Resistance Welding—The materials in this group are well adapted to resistance, spot and seam welding. The current values are somewhat greater than those required for the same thicknesses in steel and the pressures required are less. A short heat-on period is desirable as the metal is very fluid at the interfaces.

Gas Welding—With this process the flame should carry a slight excess of oxygen which tends to protect the weld metal by an impervious film of the molten silica. It is important that the base metal shall be fused simultaneously with the welding rod in order to avoid incomplete fusion or laps.

Arc Welding—This process has the advantage of highly localized heat but on account of the high fluidity of the weld metal, the work must be welded in the flat position. The carbon arc method is given preference by some operators because of its ease of control. This process is possible to some extent with position welding. The metal should be clean and covered with a suitable flux.

9. Cupro Nickel—These alloys are well adapted to fusion welding. The four sources of trouble to be overcome are: (1) The refractory unfluxable nickel oxide which causes the metal to solidify with a rough surface; (2) the tendency of the metal to absorb gas when molten and reject it when solidifying, which causes porosity; (3) the tendency toward red shortness; and (4) the danger of burning out the protective deoxidizers.

Resistance Welding—The materials in this group are readily welded by the resistance process, being rated as among the best of the copper alloys for this group.

Gas Welding—These materials can be welded by the gas welding process provided the welding rod has sufficient deoxidizer and a soft flame is used so as to allow quick solidification with minimum agitation. The weld metal will be covered with a silicon film and the weld should be kept running continuously until completed.

Arc Welding—With metallic arc welding a heavy flux coating on the electrodes is essential for sound strong welds. The carbon arc method of welding has not been applied to this material.

10. Aluminum Bronze—These alloys are, as a rule, harder and more readily forgeable than the alpha brasses. They may be bronze welded, but care should be exercised to start with a clean base metal and cover same with flux before the heat is applied.

Gas Welding—If the aluminum content does not exceed 5% the material can be readily welded by the gas welding process, using a suitable flux. The welding rod must be of correct size so that it will melt only as fast as it is puddled into the weld. The torch adjustment should, for this material, be slightly reducing.

Arc Welding—A long carbon arc constitutes the most effective method of welding the materials in this group. It forms a straight fusion weld and the deposit is enhanced by a suitable flux covering. The work should be set up so that the weld is made in as nearly as possible the flat position. The metallic arc process has not been satisfactorily applied to the materials in this group.

11. Beryllium Copper—This material is susceptible to heat treatment and will attain its maximum strength and hardness with a final precipitation heat. Therefore, the reduction of strength at the region of the weld can be greatly improved by subsequent heat treatment in that zone. This may be accomplished either by hot rolling or forging or by a homogenizing anneal. The usual brazing flux will not dissolve beryllium oxide but will tend to prevent this oxide film from forming.

Resistance Welding—The materials in this group are readily resistance, spot and seam welded using relatively light pressure and short heat-on periods.

Gas Welding—Thus far no flux or gas fusion welding procedure has been discovered which will eliminate the difficulty arising from the refractory insoluble film of beryllium oxide.

Arc Welding—The carbon arc process is considered the most satisfactory for welding this material because it is possible with a short arc and a high heat to have the weld metal flow into the base metal before the tough oxide film is formed. A thin application of flux is desirable but not essential. As the metal is extremely fluid only welding in the flat position can be performed and a copper backing-up strip is essential.

H. Aluminum and Aluminum Alloys*—The common welding methods which have been adapted to joining aluminum and the aluminum alloys, include gas, atomic hydrogen, metallic or carbon arc, and resistance welding. In each case some knowledge of the metallurgical and physical characteristics of the aluminum alloys must be considered to obtain economical results and sound joints. In the following is included a general discussion of the essential characteristics of each welding method as applied to all of these alloys.

Gas Welding (General)—The commonly used gases for welding aluminum and its alloys are oxy-hydrogen and oxy-acetylene. Equally good results from the standpoint of soundness, strength, speed and appearance are obtained with either gas. Standard equipment in the way of torches, hose and regulators are suitable for welding such materials. Some work has also been accomplished with oxy-natural gas and oxy-propane derivatives, and while good soundness and strength have been obtained in such welds, the use of these gases does not appear to be economical because of the comparatively low rate of welding.

When fusion welding aluminum, it is important that a suitable flux be used to remove the oxide coating which forms on the surface of all aluminum alloys in the atmosphere. This oxide coating does not melt at the welding temperatures and will prevent smooth coalescence of the weld metal unless a flux is provided that will melt somewhat below the welding temperatures and which breaks down the surface skin of oxide permitting the liquid metal from the rod to flow into the molten parent material. A number of good fluxes are available. These are applied either dry or by mixing with tap water to the consistency of a thick paste.

Practically all aluminum welding fluxes contain chlorides, fluorides, and sulphates. Residual deposits on the joints after welding will, in the presence of moisture, attack the base metal. Thorough cleaning is especially necessary on parts that are to be painted, as the presence of flux will lift the paint coatings over the welds. Such action can be prevented by cleaning the parts after welding by scrubbing the joints in boiling water. On tanks or parts where the joints are inaccessible, neutralization of the flux can also be accomplished by dipping for 30 min. in a 10% solution of cold sulphuric acid, or a 10 min. immersion in a 5% solution of sulphuric acid held at 150°F.

The proper choice of filler material for gas and atomic hydrogen welding is important, particularly when joining alloys with comparatively large amounts of alloying constituent. Commercially pure aluminum and metal of higher purity are generally welded with the same grade of metal as the parent material. The same practice is satisfactory for the aluminum-manganese alloys. In welding the aluminum-magnesium alloys or the aluminum-silicon-magnesium alloys, a filler rod containing 95% aluminum and 5% silicon is generally used. This rod has a substantially lower melting point than pure aluminum, and permits the dissipation of some of the stress set up by solidification shrinkage and the thermal contraction which occurs in the weld zone as it cools. Cracks in the weld and the transition zone, on parts that are welded in jigs to hold proper alignment, can be minimized by using this rod.

Arc Welding (General)—Aluminum and its alloys can be fusion welded with the metallic arc or the atomic hydrogen process. These processes have the advantage that the highly concentrated heated zone obtained with the arc prevents excessive expansion of the parts being welded with consequent lessening of distortion. In addition, the preparation of the joints for welding is simpler and the rate of welding is faster.

Because of the relative difficulty of controlling the arc, it is ordinarily not practical to butt weld material lighter than 0.06-0.08 in. thick or fillet weld joints on plate much lighter than $\frac{1}{8}$ in. thick. The soundness of the welds, particularly in thin material, is usually not equal to that of gas welds. While arc welded joints are equal in strength to gas welded joints, it requires considerable care to obtain liquid or gas tight joints in material lighter than $\frac{1}{8}$ in. thick.

Metallic arc welds can be satisfactorily made with direct current, but the proper polarity to be used should be determined by trial on the joints to be made. The capacity of the equipment and the electrode size are determined by the thickness of the material to be welded. Electrodes $\frac{1}{8}$ in. in dia. can be used on thicknesses ranging from 0.064-0.125 in. material, using amperages from 45-85; $\frac{3}{16}$ in. electrodes are suitable for thicknesses from $\frac{1}{8}$ - $\frac{1}{4}$ in. for which amperages of 85-175 will be required; for $\frac{1}{4}$ in. thickness a $\frac{1}{4}$ in. electrode and amperages from 175-225 will be

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required, while for $\frac{3}{8}$ in. thickness, a $\frac{1}{4}$ in. electrode should be used with an amperage from 225-300. In general, the use of heavy currents at high welding speeds is helpful.

Unless a suitable flux is provided, the oxide coating present on the filler rod and the parent material will prevent coalescence of the weld metal. Consequently, successful results are most easily obtained by using a coated electrode on which a heavy coating is provided that functions both to remove the coating on the metal, and to stabilize the arc. As the aluminum-silicon alloy provides superior fluidity at the welding temperatures, it is used for the filler material in all of the commercially available electrodes.

When the atomic hydrogen process is used, a good grade of aluminum flux should be used. A number are available, and, as a general rule, when mixed with water to the consistency of a thin paste should be applied to both the filler rod and the seam.

As in gas welding, the choice of filler material is important with this process and follows the same rules. Where the thickness of metal being welded is sufficient to allow the manipulation, the filler rod may be inserted in the molten pool and moved back and forth to assist in breaking up the oxide film which is present. As aluminum flows readily after reaching the molten state, care must be used to keep the molten metal from falling through. To prevent this, particularly on plates heavier than $\frac{1}{8}$ in., it is desirable to back up the weld.

Cracking can be largely avoided with atomic hydrogen welding by making a short weld about an inch long at the beginning of a seam and allowing it to cool before proceeding with the remainder of the seam. Castings should be preheated to approximately 425°F. before welding and allowed to cool slowly after the weld is completed. Sawdust sprinkled near the seam will char at about the correct preheating temperature. A powdery layer of oxide and flux gradually accumulates on the electrode clamps and may cause the arc to flow between the electrode holder tips instead of between electrodes, with resulting damage to the tips. If the ends of the electrode clamps are dipped in water occasionally, this accumulation will be dissolved.

Resistance Welding (General)—The aluminum alloys are joined in production by spot, seam, and push or flash welding methods. Sound resistance welded joints can be made provided proper welding equipment is used; the surface of the metal is prepared correctly and the proper machine settings are used in operating the equipment.

Equipment characteristics for spot welding aluminum are not basically different from those used for welding other metals, except more rigid control of time and pressure is desirable and integration of current should be done in smaller steps. In considering timing, electronic equipment that insures delivery of a definite number of cycles, and eliminates undesirable transients in the secondary circuit by making and breaking the current at the zero point on the a.c. current wave, gives best results, particularly on light gage material. Good results can also be obtained with contactor type timers, controlled either mechanically or electronically. Experience has shown also that hydraulic or pneumatic pressure mechanisms are superior for spot welding the aluminum alloys in that duplication of pressure at the tips can be obtained most accurately. Current in the secondary circuit must be relatively high in equipment for spot welding the aluminum alloys because of the high thermal and electrical conductivity of these materials. This factor is a question of machine design which should be considered in machine specifications in order that sufficient current is available.

Preparation of the surface of the material is significant, particularly from the standpoint of welding cost. The oxide coating on some alloys is sufficiently resistant to passage of the welding current to cause surface heating, with consequent alloying of the welding tip materials with the parts. This is particularly true of the heat treated alloys where the thermal operations required in heat treating increase the thickness, and consequently the resistance of the surface oxide coatings. It is desirable on those alloys where excessive tip wear occurs, to remove the oxide coating prior to welding. This can be done mechanically with steel wool or emery cloth, or with a chemical etch.

It is essential in setting up a welding operation to use welding tips that will maintain consistent current and pressure distribution during successive welds. The common method of dressing tips with a file is not suitable for spot welding the aluminum alloys. Good results in practice have been obtained by machining a contour on the tip that can be maintained periodically with a fine grade of emery held

in the fingers. A tip machined to a cone 158-165° included angle, or a tip with a hemispherical end is usually used. Spot welding tip materials should have a conductivity better than 75%, and a hardness exceeding Rockwell B 60. Calibration of the current and pressure delivered by a machine are essential to make proper machine settings.

Seam welding is a special application of spot welding in which rolls are used for electrodes, and the current is applied intermittently. Machine characteristics, as outlined above, apply as well to seam welding equipment except that successful results have been obtained only with electronic timing devices. In making liquid or gas tight joints, the timing cycle is adjusted so that the current is on not more than 30% of the time. By adjusting the timing cycle and the speed of the rolls, overlapping or intermittent welds can be made. Machine settings for seam welding depend upon the gage, temper, and alloy to be welded, and specific problems in connection with supplying suitable equipment should be referred to the machine manufacturers.

The electric butt resistance welding of all the wrought aluminum alloys is possible if a welder of proper design is available, but the aluminum-manganese and high purity aluminum are more readily welded by this method.

Simple cylindrical and rectangular sections of aluminum can be push welded. The parts to be welded are clamped in dies and pressure is applied before the application of power. Application of power causes surface melting of the aluminum and softening of the metal near the plane of contact. The joint is held under pressure by the dies, which causes the molten and soft metal to squeeze out of the joint. Power is cut off after a predetermined die travel or number of cycles of current application. Rapid freezing of the weld takes place because of conduction of heat away from the joint.

Push welds require excellent fit between the pieces being welded and between the pieces and the clamping dies. Equipment for such welding is characterized by high current capacity and rapid free movement of the movable die.

The flash butt weld process is adaptable to welding complicated extruded shapes of aluminum as well as the simpler cylindrical and rectangular shapes. The parts to be welded are clamped in dies and power is applied before the parts are allowed to come in contact. Movement of the dies together is accomplished by a motor driven cam which imparts an accelerated motion to the movable die. Flashing is maintained for from $\frac{1}{2}$ -1½ sec. during which time from $\frac{1}{2}$ -1 in. of aluminum is flashed from the parts being welded. The flashing period is terminated by the nearly simultaneous cutting off of power and a sudden increase in velocity of the moving die. The ends of the parts being welded are forced together and rapid freezing of the weld takes place because of conduction of heat to the dies.

Good fit between the parts being welded is not necessary. Dies should fit the aluminum section well enough to provide mechanical support for projections or thin sections and clamping pressure must be high enough to prevent slippage during the final push-up period.

The relation between welding time, die motion, die spacing and welding current is varied for each section and alloy of aluminum welded. Sufficient data on machine settings are not available, and for this reason it is recommended that before obtaining equipment for flash welding aluminum, tests on the particular alloy and section be made to determine the electrical and mechanical specifications for a suitable machine.

1. High Purity Aluminum—In some cases it is necessary to use material of purity higher than commercially pure aluminum, in order to obtain better resistance to certain types of chemical attack. A typical example is found in storage or fermenting tanks used in the brewery industry where a purity of 99.5% aluminum is usually applied.

Resistance Welding—These materials lend themselves readily to spot, seam or butt welding and no special practices are required. The resistance to corrosion of resistance welds is not inferior to the parent material.

Some difficulty may be experienced in attempting to spot or seam weld high purity aluminum in the soft temper on material that is heavier than 0.100 in. thick. This is apparently caused by the fact that the hardness of these materials in the soft temper is not sufficient to prevent the welding electrodes from deforming the surface, with consequent spreading of the current and pressure distribution during the welding cycle. This results in weak and inconsistent welds. This is not true in the intermediate or hard tempers of these materials.

Gas and Arc Welding—High purity aluminum requires no special treatment from the standpoint of welding technique when considering equipment, preparation of joints, or machine settings. In order to obtain comparable resistance to corrosion in the welds to that in the parent material, a filler wire of the same composition as the parent material should be used. This is frequently handled by shearing strips from the parent material. If metallic or carbon arc welded joints are to be made in these materials, special flux coated electrodes with a filler material of high purity wire should be obtained.

Welds in these materials are characterized by comparatively high ductility and dressing operations are usually carried out by hammering. A tensile strength across the welds equal to the strength of the annealed temper of the parent material is obtained on fusion welded joints regardless of the temper of the material prior to welding. Sound welded joints can be made in any of the commercial forms of these materials.

2. Commercially Pure Aluminum—Commercially pure aluminum is readily weldable by all methods. It is widely used on dairy and chemical tankage wherever the mechanical properties are adequate.

Resistance Welding—All of the commercial forms of commercially pure aluminum are spot, seam, or butt welded in production. No special technique is required for welding these materials and because of the excellent surface present on commercially pure aluminum, this is probably the most economical alloy to use from the standpoint of resistance welding cost. It is also common practice to resistance weld cast parts in which the composition has been varied to improve mechanical properties or casting qualities to articles made from commercially pure aluminum.

The previous remarks concerning the welding characteristics of the annealed temper mentioned in Section 1, apply as well to commercially pure aluminum, though to a lesser extent.

Gas and Arc Welding—This material can be both gas and arc welded, and commercial applications have been made on parts ranging in thickness from 0.020-1 in. Butt welds are characterized by high ductility in the welds and excellent resistance to impact or shock loading. A strength equal to the tensile strength of the annealed material is obtained in the welds.

Commercially pure aluminum is generally used as a filler material when making welds and considerable testing and practical use has indicated that the resistance to corrosion of such welds is substantially equal to that of the parent material. Metallic arc welding is generally done with standard flux coated electrodes containing Al-Si filler rod. However, where maximum resistance to chemical attack is important, a special coated electrode containing commercially pure aluminum filler material should be used.

3. Al-Mn Alloy—This alloy is substantially the same as commercially pure aluminum from the welding standpoint, except that the mechanical properties of both the parent material and of welded joints are higher.

Resistance Welding—In this case also, no difference is apparent in the technique of welding this alloy compared to commercially pure aluminum. The strength of the welds, however, is higher.

Gas and Arc Welding—This alloy is widely used where higher strength than can be obtained in welded parts made from commercially pure aluminum is required. The previous remarks on filler wire and resistance to corrosion apply as well to this material.

4. Al-Mg-Cr Alloy—By alloying aluminum with magnesium and chromium, a material is available with considerably higher mechanical properties than can be obtained with the previously mentioned alloys. This introduces some problems, particularly from the standpoint of fusion welding, which are described in the following.

Resistance Welding—This alloy can be readily spot, seam or butt welded and because of the high strength and hardness, no difficulty is experienced with any temper. Some of the commercial forms, particularly the annealed sheet, are covered with an oxide coating that will cause wear on the welding electrodes unless it is removed prior to the welding by mechanical or chemical means. The strength of spot and seam welds in this alloy is higher than that obtained with the previously mentioned materials. Spot welding this alloy has found wide application for assembling airplane gasoline tanks.

Gas Welding—This material is more sensitive to the application of the welding heat in that cooling cracks, caused by the thermal contraction and solidification shrinkage may occur when the weld cools. This condition is minimized if a filler

material of lower melting point than the parent material is used, and practically all gas welding is done with an Al-Si filler rod. The above condition is not serious when the thickness of the parts is such that welds can be made in one pass. Consequently, most commercial applications have been made on material up to $\frac{1}{4}$ in. thick. Welded joints in thicker parts will usually require some preliminary trial to determine a method that will cause the least stress in the welds during the cooling period.

The strength of welds in this alloy is generally equal to the strength of the annealed material, but the elongation in the welds is substantially lower than that obtained on commercially pure aluminum or the Al-Mn alloy.

Arc Welding—The above remarks do not apply to joints made with the metallic or carbon arc welding processes. In this case the welding heat can be concentrated to a narrow zone and the difficulties from cracking as the weld cools are practically eliminated. The standard arc welding technique using Al-Si filler wire in the electrodes is generally used for arc welding this alloy.

5. Al-Mg-Mn Alloy—This alloy is similar, from the welding standpoint, to Al-Mg-Cr alloy just described, and the welding characteristics as described can be applied in this case.

6. Al-Si-Mg Alloys—These alloys rely for their strength on heat treatment operations in which the material is treated thermally so that the metallurgical structure is arranged to obtain comparatively high mechanical properties. It follows that the application of welding heat may partially obliterate the heat treated structure with consequent lowering of properties.

Resistance Welding—These alloys are widely used for resistance welding applications, particularly of the type where structural sections are spot welded to sheet panels to stiffen the panels.

Because of the heat treating operations applied to these alloys, an oxide coating is usually present on the surface which interferes with the passage of the welding current. In order to prevent surface heating between the parts and the welding tips, mechanical or chemical cleaning operations are performed on the surface contacting the welding tips prior to welding.

Gas Welding—All of these alloys can be joined with the welding torch. A width, in the parent material, from two to five times the thickness of the material has been effected by the heat in this method of welding. Reheating after welding will increase the strength of the joint, but because of the cast structure in the weld, a strength equal to the parent material is not obtained. The strength of a gas welded object of these alloys is usually not predictable as the annealing effect of the welding heat is dependent on the amount and location of the welds in the parts. Mechanical tests on the welded parts are usually carried out to determine the suitability of the welded assembly for the service intended.

The welding technique is substantially the same as for other materials and the resistance to corrosion of welded joints is good. Filler wire of Al-Si is usually used.

Arc Welding—Because of the comparatively narrow zone affected by the welding heat, less difficulty is experienced from cooling cracks when these alloys are assembled with the metallic or carbon arc. The strength of the welds, however, is approximately the same as that obtained with the gas torch and the previous remarks made in connection with gas welding apply as well to arc welded joints. Flux coated electrodes containing Al-Si filler wire are used for arc welding these alloys.

7. Al-Cu-Mg-Mn Alloys—This group of materials contains the aluminum alloys in which the strength is increased to a maximum by heat treatment operations. The effect of welding operations is, with two exceptions, to reduce the resistance to corrosion and mechanical strength. Consequently, these materials do not find extensive use in welded parts.

Resistance Welding—These alloys can be assembled by spot, seam or butt welding with good results, from the standpoint of static mechanical strength. Exposure tests on resistance welds have indicated that the resistance to corrosion of the welds is not equal to that of the parent material. Protection by paint is essential to insure lack of deterioration in the joints from corrosion. It is important in some applications, particularly aircraft structures, that the resistance to corrosion of spot welds be as good as the parent material in the high strength alloys. This is obtained by providing a surface on the alloys of high purity aluminum that protects the material from corrosive influence. For this purpose aluminum clad materials have been produced and considerable testing of spot welds exposed to corrosive

conditions has indicated that welds can be made in these alloys that have corrosion resistance equal to the parent material.

Gas Welding—Both the strength and resistance to corrosion of welds in these alloys are substantially lowered by gas welding.

Arc Welding—The previous remarks on gas welding apply to metallic and carbon arc welding of these alloys. However, when the welds can be placed in the structure where the stresses are low, these alloys can be arc welded. As the welding heat may affect the structure of the alloy, it is suggested that welded parts be tested prior to use.

I. Nickel and Nickel Alloys*—Nickel and the high nickel alloys are welded by the methods commonly used for the joining of steel (oxy-acetylene, metallic arc, carbon arc, resistance welding, and flash welding methods).

1. Rolled Nickel—Resistance Welding—The spot, seam or stitch and projection welding of this material is readily done. One practical application of the spot welding of nickel is the internals of radio tubes.

Gas Welding—This material is readily gas welded using the oxy-acetylene flame. The filler metal should be a bare nickel gas welding rod made for the gas welding of wrought nickel, and with which no flux is used or needed. The oxy-acetylene flame should be slightly reducing with a $\frac{1}{8}$ in. excess acetylene feather. The envelope of the flame serves to preheat the unwelded seam (forehand welding), with the welding rod kept within the flame envelope to avoid undue oxidation of the heated end of the rod. It is not necessary topeen the gas weld when it is either hot or cold, as there is no porosity present. Certain types of fabricators still prefer to cold work welded equipment—a procedure which is not harmful if care is taken to avoid excessive cold work. The deposited metal is extremely ductile and can be cold worked in later forming operations.

Arc Welding—A nickel welding electrode with a heavy flux to protect the weld metal as it passes from the electrode through the arc to the plate being welded is required. No flux other than that on the electrode is necessary. Nickel is satisfactorily welded using reversed polarity, that is, with the electrode positive and sheet negative, and with a short arc—24-26 volts across the arc. Welding can be done in any position—the flat or downhand, vertical or overhead positions. Tensile strengths of arc welded butt joints in nickel are of the order of 60,000 psi. min. with satisfactory ductility.

Carbon Arc Welding—A small dia. carbon, $\frac{1}{8}$, $\frac{3}{16}$, or $\frac{1}{4}$ in. in dia., tapered about 2 in. to a pencil point is used on straight polarity with a short arc. The carbon arc merely supplies the heat and is either used to fuse together edges or is used with a lightly fluxed nickel filler rod.

Silver Brazing—Silver brazing is easily done using the low temperature brazing alloys and appropriate silver brazing fluxes. The use of borax as a flux is to be avoided as it affords insufficient protection, while the low flow point solders are melting.

2. 67% Ni-30% Cu Alloy—Resistance Welding—With spot, seam, stitch or projection welding, high current densities flowing for short times, less than 15 or 20 cycles, are preferred. Pressure should be just sufficient to hold the metals in contact to prevent arcing or undue spatter.

Gas Welding—The gas welding of this alloy is done with a gas welding wire of the same composition and a gas welding and brazing flux designed for this alloy. A slightly reducing flame is required as with nickel and under this flame the weld metal is very fluid. Position welding is regularly done on pipe lines. The pool of molten metal is not to be puddled or boiled as this may introduce harmful oxides which in turn may embrittle the weld.

Metallic Arc Welding—The electrode for the metallic arc welding of wrought and cast forms of this alloy consists of a wire with a core of the same composition as the alloy with a heavy flux covering.

Reversed polarity with the electrode positive and the plate negative is required for welding in the downhand, vertical, or overhead positions. Regardless of the position of the work, the electrode is held approximately normal to either the plate or the surface of the pool of molten metal.

Tensile strengths are of the order of 70,000 psi. min. and elongation in free bend 30% minimum, with nick break tests, and X-ray examinations satisfactory.

Carbon Arc Welding—A small dia. carbon pencil, $\frac{1}{4}$ in. or smaller, is ground to a long taper and gripped in the electrode holder in a straight polarity welding

*By Frank Flocke, International Nickel Co., New York.

arrangement. A welding rod of the same alloy with a light coat can be used where filler metal must be added to the joint. In other cases, the carbon pencil may be used to make an edge weld by melting the flanged edges of sheet metal, in which case no filler rod is added. This joining method is particularly useful for melting down the ends of thin walled tubes projecting beyond the surface of tube sheets or in welding this alloy of the order of 0.050 in. or 0.062 in. in thickness where a minimum of finishing is required.

3. 79% Ni-13% Cr-6% Fe Alloy—Resistance Welding—The notes in the section above on the resistance welding of the 67-30 Ni-Cu alloy apply equally in the present case of joining this Ni-Cr-Fe alloy.

Gas Welding—A welding rod of the same composition as the material being welded should be used. Since the oxides of chromium are refractory and tend to interfere with gas welding if not fluxed away, a flux suitable for chromium bearing nickel alloys will be found useful. Sound, ductile welds are easily made with a moderately reducing oxy-acetylene flame and appropriate welding rod and flux.

Metallic Arc Welding—An electrode of the same alloy with a suitable flux coating is used in making arc welded joints. This alloy is regularly welded using reversed polarity. Welds are strong and ductile.

4. Ni-Cu-Al Alloy—Resistance Welding—The information given above on the resistance welding of the Ni-Cu alloy applies equally to the spot and seam welding of this Ni-Cu-Al alloy.

Gas Welding—The use of a special flux applied in the form of a water paste is required to produce sound gas welds. The heated end of the filler rod of the same alloy must be kept within the protecting envelope of the oxy-acetylene flame to prevent oxidation of the aluminum constituent of the rod. A strongly reducing flame is required.

Metallic Arc Welding—As this is a nonmagnetic, heat treatable alloy, welds made in this material must have similar characteristics, thus necessitating the use of a coated electrode of the same alloy. Metallic arc welds can be annealed or hardened by heat treatment.

Silver Soldering—Care must be taken when preparing this alloy for silver soldering to have all edges smooth to avoid any sharp notches, or cracking will result because of the hardness of the metal. A low temperature silver brazing alloy melting about 1175°F. is preferred.

J. Lead—Jointures in lead have been made for many years by a process known as lead "burning" for sheets and plates, and lead "wiping" for pipes and irregular sections. The term "lead burning" is, however, a misnomer, as the lead is not burned but is fusion welded by application of a suitable flame, either with or without the addition of filler metal.

Lead is a material of high density but low melting point (621.3°F.) in its commercial forms. By alloying with antimony, bismuth, cadmium or tin, its physical properties can be greatly changed, including the melting point. Due to its relatively low range of melting temperatures, it is difficult to manipulate under the welding flame, and if the operator is not careful it is only too easy to burn holes through the material being joined.

Two forms of joints are used with sheet lead, the butt and the lap types. With the butt type the edges of the plate do not need to be beveled unless the plate is of considerable thickness, in which case the edges are beveled to an included angle of about 30°. The edges of the plates to be welded are scraped clean and bright on both sides to remove all lead oxide for a distance of about ½ in. back from the edges. This is usually accomplished by use of a sharp shave hook. For welding the edges are placed close together, then tacked at points about 1 ft. apart and the V is filled in with molten lead fused with the flame from the end of a lead filler rod. The seam is usually filled in with lead to give some reinforcement, particularly on heavy plates.

In making lap joints the edges are cleaned of lead oxide on both sides for a width considerably more than the width of overlap, using a sharp shave hook. The sheets are lapped from ½-1½ in. according to the thickness of the plate and the strength of the joint that is required. The welding flame is used to fuse the plates by melting out a section of the upper sheet edge which flows down and joins into the lower sheet. The flame is carried forward by a succession of in and out and progressive movements which is for the purpose of distributing the heat and preventing burning through the plate at any one point. Great care must be taken in manipulating the flame so that a small portion of the overlapping sheet is welded

at a time in view of the probability of liquid lead running off and dropping. This requires careful adjustment of the torch to give exactly the desired size of flame and careful manipulation by the operator to hold the surface metal near the fusing point and still avoid rendering the material too fluid.

The cross section of the lead filler or "burning bars" depends on the thickness or weight of lead to be welded; $\frac{1}{8}$ in. wire size is recommended for 2 and 3 lb. lead; $\frac{1}{4}$ in. for 3½-5 lb. lead; $\frac{3}{8}$ in. for 6-8 lb. lead; and $\frac{1}{2}$ in. and $\frac{3}{4}$ in., depending on the type of seams, for 10, 12, 16 and 20 lb. lead.

The importance of using lead welding rods of the correct size for each weight of lead can hardly be over-emphasized. If the bar is too light, the time required to fuse the lead needed for each deposit permits oxidation to take place due to the fact that the metal is light and is likely to be overheated. If a heavy bar is used with a small flame, the metal does not melt sufficiently to carry on the seam, and the seam chills during the lost time period while the flame is melting the lead. Fusing the filler is done over the sheet of course, and the time interval between fusing the burning bar and depositing it on the sheet must be carefully gaged.

K. Magnesium Alloys*—The chief methods employed are gas welding, electric resistance seam and spot welding, and electric resistance butt welding. The magnesium sheet alloys have good oxy-acetylene welding characteristics. Cast, extruded or forged fittings to be welded into magnesium sheet structures should be of the same alloy composition as the magnesium sheet.

The approximate compositions of the standard wrought magnesium alloys, suitable for welding, are as follows:

No.	Al	Mn	Zn	Mg
1	4.0	0.4	...	Balance
2	3.0	0.4	1.0	"
3	.	1.5	...	"
4	6.5	0.3	0.75	"
5	6.8	0.3	1.25	"

In the extruded form the first two alloys above are also readily oxy-acetylene welded. The third alloy is weldable only in relatively short seams. The gas welding of other extrusion alloys, while possible to a limited extent, is at present not recommended.

Gas Welding—The oxy-acetylene flame offers a protection to the molten metal due to the formation of a protective atmosphere. Welding magnesium alloys with the oxy-hydrogen flame requires considerably more skill and is therefore not recommended. The procedure, so far as the manipulation of the flame is concerned, is similar to that employed for aluminum and other metals. It has frequently been found that magnesium parts can be welded more rapidly than aluminum, due to their lower heat capacity. Holding the flame sideways at an angle of 30-45° to the work will produce the best results. When welding thin sheet, this angle should not exceed about 30° to keep the flame from burning holes in the sheet.

The welding rod should in general be of the approximate composition of the work to be welded. The size of welding rod should bear a relation to the thickness of sections for which they are to be used as follows: $\frac{1}{8}$ in. rod should be used for thicknesses up to 0.060 in.; $\frac{3}{16}$ in. rod for thicknesses from 0.050-0.110 in.; $\frac{1}{4}$ in. rod for thicknesses from 0.100-0.220 in., and $\frac{5}{16}$ in. rod for thicknesses of 0.200 in. and over.

After welding traces of welding flux should be carefully removed from the unused portion of the welding rod. Strips cut from sheet may be used instead of welding rod if no rod is available. Welded seams made with strip, however, are less uniform than seams made with rod.

A special welding flux supplied by the producers of the alloys is advisable for welding magnesium. The flux is applied to the welding rod and to the parts to be welded. As the welding flux must be completely removed after welding, only butt welding is permissible. Lap welds or any type of weld that may produce pockets or corners where flux might become entrapped must be avoided. Illustrations of this type are shown in Fig. 1. Instead, the joints should be designed as shown in Fig. 2.

The pieces to be welded must first be carefully fitted. Oil or grease should be removed from the areas to be welded with naphtha, gasoline, carbon tetrachloride or

*By H. Menking, American Magnesium Corp., Cleveland.

hot alkaline cleaners. The edges of sheet to be welded and the adjacent part of the sheet surface (about $\frac{1}{4}$ in. wide) should then be carefully cleaned and brightened by wire brushing, filing, or scraping. The joints to be welded require different preparation depending on sheet thickness, in accordance with Fig. 3. Sheet of thin

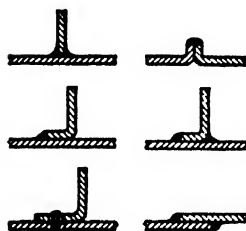


Fig. 1

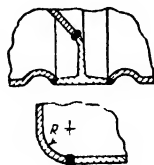


Fig. 2

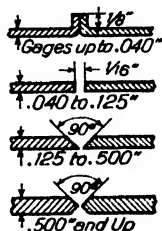


Fig. 3

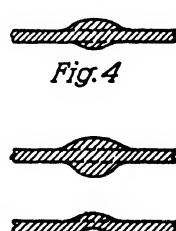


Fig. 4

Fig. 5

gages (up to 0.040 in.) is flanged about $\frac{1}{8}$ in. as shown in Fig. 3, and the flange is welded down into a plain butt. For heavier gages, from 0.125 in. and greater, it is advisable to notch the edges with a cold chisel to facilitate penetration of the weld. The notches should be about $\frac{1}{8}$ in. deep and $\frac{1}{8}$ in. apart.

Castings or extrusions can be welded to sheet if their section is reduced by filing to the approximate thickness of the sheet to which they are to be joined. Sections of slightly different thickness may at times be welded to each other if the heavier section is preheated, so that both edges of the seam will begin to melt and flow at the same time. Rivets of aluminum alloys, when used in magnesium construction, must not be welded over as this results in a brittle alloy of uncertain composition.

Welding Procedure—After fitting and cleaning the pieces to be welded, they should be preheated with the torch to about 500-600°F. and the flux applied to the sheet edges and to the rod. The seams should next be tacked at intervals of from $\frac{1}{2}$ -1 $\frac{1}{2}$ in., depending on the type of work. A distance of 1-2 in. is then completely welded on each end of the weld in order to minimize warping in the subsequent welding of the seam. Any sheet which tends to warp during tacking should then be straightened out with a wooden hammer while it is hot. After reheating the sheet and covering the tacked spots with flux, the entire seam should be completed and the sheet again straightened with a wooden hammer.

In order to obtain a smooth weld, it is desirable to keep the welding wire in the molten pool of metal and not remove it any oftener than necessary. To accomplish this, sufficient flux should be applied to the work and to the welding wire before welding so as to avoid the necessity of frequently renewing the flux on the welding wire. If any portions of the weld should begin to oxidize, the work must be stopped and the oxidized portion carefully scraped or filed out. The cross section of a proper weld is shown in Fig. 4. Welds with cross sections as shown in Fig. 5 should be avoided.

Weld Cleaning—After welding, the flux must be carefully removed with hot water and a wire brush. The welded part should then be given the chromium pickle or dichromating treatment. This treatment is applied by dipping for about 1 min. in a solution made according to the following formula:

Sodium dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$).....	1.5 lb.
Concentrated nitric acid (sp.gr. = 1.42).....	1.5 pints
Water.....	to make 1 gal.

The welded article is then allowed to drain, rinsed in cold running water and placed for at least 2 hrs. in a container with hot water containing about 0.5% sodium dichromate. Finally the part should be carefully dried, preferably with a heated air blast. Lacquering of the completed seam is an excellent precaution and insures stability.

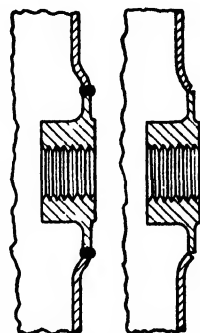


Fig. 6

Electric Resistance Welding—Spot, seam or butt welded joints are used to an increasing extent in magnesium structures. They combine high strength with economy in operation. The absence of any welding flux insures stability without any special precautions.

Magnesium sheet and extrusion alloys spot weld satisfactorily. The different alloys of sheet and extrusion alloys may be spot welded to each other, although the use of the same alloy is preferred. Magnesium sheet may also be spot welded to magnesium alloy castings of not more than about $\frac{1}{4}$ in. wall thickness.

Ordinary copper is unsatisfactory for electrodes as the high pressure employed distorts the contacting surface. This deformation can be avoided by using one of the special hard high conductivity, copper-base alloys made for this purpose. The tips of the electrode should be kept clean by frequent dressing to obtain uniform results and to avoid a rough surface of the spot and alloying of the tip material with the sheet.

Both the surfaces to be welded and those contacting the electrodes should be cleaned of oil and dirt and brightened with sandpaper, emery cloth, or by wire brushing before welding is started.

After welding, the spots should be wire brushed and dichromated. The two hour period of immersing in hot water, as applied on gas welds, may be dispensed with, as no welding flux is used in spot welding.

Electric seam welds may be used on all sheet alloys and most of the extrusion alloys. For seam welding, equipment with the same general characteristics as described for spot welds is required, the main difference being that the electrodes are power driven rollers. Electronic timing equipment is used to provide interrupted power impulses. Electric seam welds may be of the continuous or the intermittent type. The continuous seam weld which is really a succession of overlapping spot welds will produce gas tight joints. The intermittent seam weld produces joints similar to spot welds, but at lower cost since the operation is faster and fully automatic. Recommendations given under spot welding for cleaning of the electrodes and the magnesium parts to be welded also apply to seam welding.

Successful resistance butt welds may be made in extruded sections of the standard magnesium extrusion alloys (6.5% Al, 0.75% Zn, 0.3% Mn alloy and 4% Al-0.4% Mn alloy) and tensile strengths of about 26,000-43,000 psi. with 3-8% elongation, depending on the size and shape of the welded section, are obtained. Best results are obtained with a combination of flash and push welding in which, after the initial melting, the ends to be welded are rammed together by a predetermined amount controlled by a cam. Straight push welding in which the pressure is exerted by air or by hand is not recommended. The amount of current used is considerably lower than that used for aluminum. Many sizes of bars and various shapes ranging from 0.080-1 in. in thickness and from 0.150 in. to 1.0 sq. in. in cross section have been successfully welded by this method.

Welding of Castings—Minor defects in magnesium alloy castings such as sand holes may be repaired by oxy-acetylene welding provided that the casting is not to be highly stressed in service. To prevent cracking, the casting to be repaired should be heated to about 600°F. For more complicated castings, slow heating in an oven to avoid cracking is essential and the rate of heating should not exceed 100°F. per hour. Simple castings only may be heated with a gas flame. Immediately after welding, the casting should be put back in the oven to insure slow cooling. The rate of cooling should not exceed 100°F. per hour to avoid cracking.

The portions to be welded must be cleaned with a chisel or file and the outside oxide layer removed with a wire brush or scraper. The edges should be beveled or notched unless the wall is extremely thin (about $\frac{1}{8}$ in.). On walls of $\frac{1}{2}$ in. thickness or more, beveling both sides as shown in Fig. 3 is recommended. If a larger sized groove is to be welded, a suitable cast plate with beveled edges should be provided and fitted to the groove with $\frac{1}{8}$ in. play and welded in place.

The flux is brushed on the edges to be welded and on the welding rod. Because the density of the molten magnesium is close to that of the flux, care should be taken to prevent the freezing of any flux in the body of the weld. Blowing through the pool of molten metal with the flame after welding, will help to bring entrapped particles of flux to the surface.

After cooling down, the repaired portions should be thoroughly cleaned by scrubbing with hot water and a wire brush to remove all traces of flux. The built-up portion of the seam should then be ground down or machined off and again scrubbed with hot water and a wire brush. The casting should then be "dichromated," rinsed in cold water and kept in boiling water with 0.5% sodium dichromate

for 2 hr. Following this the casting should be placed in a steam chamber or above a container with boiling water for 24 hr., which treatment will bring out any traces of flux which may have escaped the cleaning. Castings showing flux spots on the weld after this period should not be returned to service but again put through the above washing, brushing and dipping treatment.

Welding castings requires more skill and care than welding magnesium sheet and extrusions as the sections are heavier, making the elimination of flux inclusions more difficult. However, by carefully following the above recommendations, good results can be obtained in repairing surface defects in lightly stressed castings. Highly stressed castings should not be welded. The strength of welded seams in castings of $\frac{1}{4}$ in. wall thickness is about 21,000 psi. with an elongation of 1-2%. Heat treating the welds is at present not recommended.

Stress Relieving—In the fabrication of welded members, varying degrees of stress may be set up within the metal adjacent to the welds, depending upon the size and thickness of the adjoining sections, the number of welds, their location, and the welding procedure. Members subjected to stress may be given a suitable heat treatment, usually in the form of a low temperature annealing (below the critical point).

This form of heat treatment, which is commonly referred to as "stress relieving", removes the greater part of the stresses set up by the welding operations. It involves heating the welded members to a temperature of from 1100-1200°F.

This "stress relief" treatment consists of heating the welded part uniformly to a temperature of at least 1100°F., holding it at that temperature for one hour for each inch of thickness of the thickest part welded, and then slowly cooling it in the furnace down to at least 200°F., after which it may be cooled in the air. It is not advisable to raise the temperature at a rate of over 125°F. per hour and the maximum temperature should not exceed 1200°F. The parts should be so loaded in the furnace as to be free from deformation.

In this connection it is of interest to note the requirements of the Am. Soc. Mech. Engrs. Unfired Pressure Vessel Code for stress relief of welded structures, which reads as follows:

All fusion welded vessels constructed in accordance with Par. U-68 (Class 1), shall be stress relieved. Vessels constructed in accordance with Par. U-69 (Class 2), shall be stress relieved where both the wall thickness is greater than 0.58 in., and the shell diameter less than 20 in., and for other wall thicknesses and shell diameters, where the ratio of the diameter to the cube of the shell thickness is less than 100.

Where stress relieving is required it shall be done by heating uniformly to at least 1100°F., and up to 1200°F. or higher, if this can be done without distortion. The structure or parts of the structure shall be brought slowly up to the specified temperature and held at that temperature for a period of time proportioned on the basis of at least one hour per inch of thickness and shall be allowed to cool slowly in a still atmosphere.

The structure shall be stress relieved by any of the following methods.

- (1) Heating the complete vessel as a unit.
- (2) Heating a complete section of the vessel (head or course) containing the part or parts to be stress relieved before attachment to other sections of the vessel.
- (3) In cases where the vessel is stress relieved in sections, stress relieving the final girth joints by heating uniformly a circumferential band having a minimum width of six times the plate thickness on each side of the welded seam in such a manner that the entire band shall be brought up to the temperature and held for the time specified above for stress relieving.
- (4) Nozzles or welded attachments for which stress relief is required, may be locally stress relieved by heating a circular area around the nozzle or attachment provided any part of the welded edge thereof is not less than $12t$ (t = thickness of plate) from the nearest adjacent welded joint or other element that would tend to restrict the free expansive movement of the heated area. The outside dimensions of this annular ring to be heated shall be at least $6t$ away from the outermost weld but not less than 5 in., and the entire area shall be heated simultaneously.

Bronze Welding—The term *bronze welding* is understood by the welding operator to refer to the joining of the high melting point metals, such as cast iron, nickel, and copper, by the use of bronze weld metal. Actually, the word "bronze" is not correct, as the alloys are in some cases brasses. For many welding applications, bronze welding offers advantages of speed, economy, and ability to do jobs which might otherwise be difficult or impossible.

Bronze welding is essentially an application of the oxy-acetylene process in which the joints produced are not true fusion welds, as the base metal is not melted, although a molecular union is evidently formed between the deposited metal and the base metal as explained below. Bronze forms a strong bond with metal surfaces which have been heated to the proper temperature and treated with a suitable flux. A properly made bronze weld is quite comparable in strength to a true

fusion weld. The heat required for the preparation of the edges to be joined and the melting of the welding rod is supplied by the oxy-acetylene flame. Because of the lower melting point of the rods used for bronze welding as compared with that of the material to be joined and the fact that the parts to be joined are required to be brought up only to a temperature where tinning and amalgamation with the bronze takes place, a much lower welding temperature is required in, for instance, the bronze welding of steel than in the making of a steel fusion weld.

Bronze welding with the electric arc may be accomplished by using a carbon arc and bronze or Monel metal filler rod, the arc being directed on the filler metal. Ferrous metals may be welded with bronze or Monel metal electrodes with the metallic arc process, although in this case, fusion of the base metal results. It should be noted, however, that the depth of fusion is not great.

Physical Nature of the Bronze Base Metal Bond—The character of the bronze base metal bond, which produces an adherence of bronze to base metal, in the case of cast iron, stronger than the base metal, has been investigated. It has been found that three distinct forces act to maintain adherence of the bronze to the base metal.

(1) **Tinning**—A clean metal surface will receive a thin film of a molten metal of low surface tension. The bond thus produced depends on the action of molecular forces at the bronze base metal interface.

(2) **Alloying**—A diffusion of the bronze constituents, copper, zinc, tin, and others into the base metal, and a corresponding diffusion of base metal constituents into the bronze takes place in a narrow zone at the bronze base metal interface. The base metal crystals, at the interface, when examined under the microscope, show that there is a diffusion of the bronze constituents into the crystal grains, and an alloying of the bronze metals with the base metal.

(3) **Intergranular Penetration**—The action of the molten bronze on the base metal surface opens up the crystal grain structure of the base metal surface and allows the bronze to penetrate the base metal along the grain boundaries. This alloying and intergranular penetration effect accounts for the great strength of the bronze base metal bond, which can be produced without surface fusion of the base metal.

Bronze Welding Rods—The bronze welding rod should tin readily when used with a suitable flux. It should be capable of building up a deposited metal that is practically free from defects due to slag inclusions, or blowholes. The fumes from zinc or other ingredients of the bronze should be kept at a minimum since they may interfere with the operator.

In general, the rods have a copper-zinc ratio of 60 to 40 and contain additions of tin, iron, manganese, or silicon, which improve the flowing qualities, deoxidize the weld metal, decrease the tendency to fume, and increase the hardness of the deposited metal for greater wear resistance.

For use with the arc process, a phosphor bronze or Monel electrode may be used. When heavily coated electrodes are used, the coating aids in promoting easy flow of metal.

Physical Properties of Bronze Welds—When the usual copper-zinc-tin rod is used for welding steel, a tensile strength of about 41,000 psi. on unreinforced coupons can be readily obtained. The fracture is usually through the weld metal and shows some porosity, although the general quality of the metal is good. When the manganese bronze rods are used, the strength may be somewhat greater, averaging about 46,000 psi., but the porosity in the metal is somewhat increased.

Typical Bronze Welding Test Data (Oxy-Acetylene)

Type of Coupon	Alloy	Psi.		% Elongation 2 in.	Bend Test	Brinell
		Yield Point	Ultimate Strength			
All weld metal	Copper-tin-zinc	13,500	46,500	25.0	.....	68-72
As deposited	Manganese bronze	17,000	48,000	8.0	.....	74-79
Bronze welded	Copper-tin-zinc	40,000	41,000*	....	10-12	.....
Steel coupons	Manganese bronze	41,000	46,500*	....	10-12	.....

*All average of 5 coupons. Reinforcement removed from all specimens.

Advantages—There are several advantages for bronze welding. Because of the lower temperature at which the bronze can be added to the base metal, there is an increase in speed of making the joint, and less heat is required than to make a

true fusion weld. Metallurgically the bronzes have a characteristic of yielding readily as they cool until the temperature is below 500°F., and there is an appreciable yielding under reasonably low stresses even at atmospheric temperature. This yielding as a single operation does not weaken the deposited bronze metal. Therefore, locked up stresses are reduced materially in a casting that has been welded with bronze.

Bronze welding should not be used where the finished work is to be subjected to temperatures above 500°F. It has also been learned that bronze should not be used where relatively high stresses such as 15,000 psi. may be applied to the finished work with such rapidity as to cause fatigue of the metal. Inasmuch as iron castings are seldom subject to stresses in excess of 5,000 psi., this effect can never be an important one in the bronze welding of cast iron. This same comment can be made with regard to bronze welding of malleable iron.

Inspection and Testing of Welds—Large installations of equipment fabricated by fusion welding are generally made under some form of purchaser inspection. In some welding applications, the inspection is called upon to conform to some code of construction requirements, and tests are specified to govern the qualification of the welding operator or the quality of the welding performed.

The tests that have been devised include destructive tests and nondestructive tests. Only the destructive tests are definitely quantitative, as the nondestructive tests are indicative of quality only, and some of these are indicative only to a limited extent. The destructive tests embrace the following: Tensile, bend, specific gravity, nick-break tests, impact, and hardness tests. The nondestructive tests that have been used on welded joints embrace the visual, the stethoscope, X-ray, and gamma ray tests; electric resistance and magnetic tests have been developed and are being used successfully in many instances. The hydrostatic proof test is a form of nondestructive test that is used for pressure vessels and closed containers.

Visual inspection of fusion welding while in process is also possible, although not generally specified directly. For this the fusion welded joint offers the peculiar advantage in that the inside of the joint may be observed while it is being made. Visual inspection requires a careful observer, properly trained, but it is valuable in studying procedure. The inspector watches the rod or electrode and observes how it melts down, notes the fusion and penetration and listens to the sound of the arc, or observes the flame adjustment of the torch. All of these items properly studied and understood will give a skilled inspector considerable information regarding the quality of the weld under observation.

Tensile Test—The tensile specimen of the joint is usually taken transversely with the weld in the center of the specimen, which conforms to the A.S.T.M. standard for flat plate tensile specimens, Fig. 7. The weld reinforcement may be removed or not, depending on the information sought.

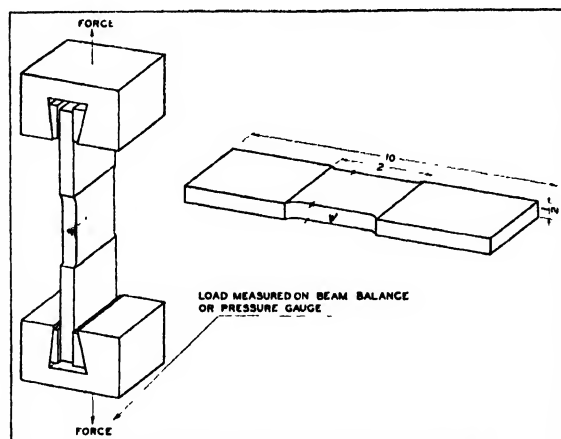


Fig. 7—Tensile specimen for testing welds.

It is customary to obtain from the tension test the yield point and elongation. For high quality welds the yield point will be that of the base metal and the elongation will be of little value, particularly when the weld is stronger than the plate. The ductility of the weld metal in such cases is best obtained by means of the free bend test.

In order to obtain the tensile strength, yield point, elongation, and reduction of area of the weld metal, all weld metal specimens are taken longitudinally from the weld. The specimen can be taken only from welds in plate $\frac{5}{16}$ in. thick or

more. Smaller proportionate specimens can be taken from welds in thinner plate, a $\frac{1}{2}$ in. diameter specimen with 1.5 in. gage length may be used. The all weld metal tension test piece gives reliable data as to the physical properties of the weld metal, and is required by the Am. Soc. Mech. Engrs. Code and by the Am. Welding Soc. Specifications for filler metal.

For evaluation of fillet welds a tension test is commonly applied to a specimen formed by fillet welding two splice bars to opposite sides of two butted test bars, the fillet welds being made either longitudinally or transversely along the edges of the splice bars; in either case the resulting failure of the fillet weld is a shear failure and the stress is recorded in pounds per lineal inch, which for any average size of fillet, serves as a ready means of comparison.

In the case of thin wall welded tubing it is of course impossible to obtain the regulation tensile test specimens and a drift test (Fig. 8) has been devised to determine the strength of the weld. This simple test consists of forcing a tapered hardened steel drift into the end of the longitudinally welded tube. It may be driven by a hammer, or forced in with a press, which method is more desirable since it eliminates the factor of shock. The tube end is gradually expanded until failure occurs by splitting, usually outside the welded area, showing the weld to be stronger

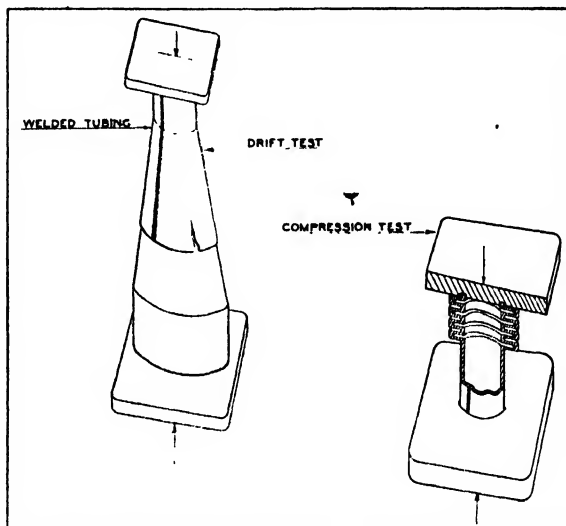


Fig. 8—Drift and compression tests for welded tubing.

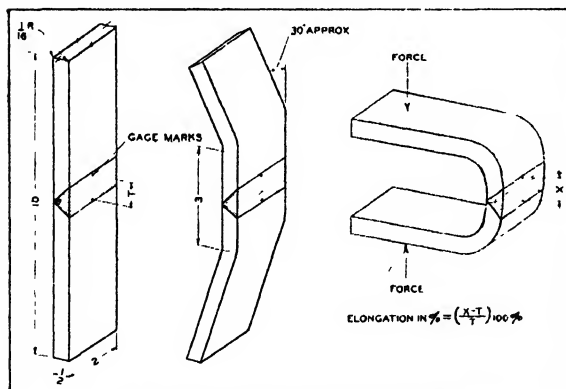


Fig. 9—Bend test for testing welds.

than the base metal and to have adequate toughness and ductility. The distance the drift is forced into the tube may be taken as a measure of the ductility of the welded tube. Since this test stretches the welded joint, its action is quite similar to that of the tensile test.

If a short length of welded tubing is placed axially in a compression machine and loaded, it will collapse like a bellows, and in so doing will be subjected to shear, tensile, and bending stresses. This qualitative test for ductility

affords a good evaluation of the flanging qualities of the welded tube. Of course, a simple flanging operation will be an adequate test of the ability of the welded tube to withstand flanging operations, but this test is not so severe as the crush test. The hydrostatic test to destruction which is applied in some instances to pressure vessels and closed containers to determine their ultimate strength, as well as also the character of their failure, is an extension of the tensile test. It is a form of test, however, that can be applied only in connection with design studies and research and it is not necessarily a test of the welded joint, as the vessel may rupture at a place apart from the weld. This test is intrinsically a test of the entire

structure and will reveal the weakest part or place, whether it be the weld or the solid metal.

Bend Test—Since the tensile test in flat specimens gives no quantitative measurement as to the ductility of the welded joint, the free bend test was devised to furnish this much needed information. The free bend tests yield quantitative data independent of the thickness of the specimen provided the width is at least three times the thickness. However, the Am. Soc. Mech. Engrs. Code calls for a width one and one-half times the thickness.

Fig. 9 shows the design of the bend specimen and the method of preparation. After the initial bends are made, the specimen is placed as a strut in a vise or press and bent until failure occurs on the outside bent surface between the gage marks. Corner cracks are not considered failures. Any failure on the surface is not considered as such until its greater dimension is $\frac{1}{8}$ in. or more. The elongation of the outside fibers is measured directly with a flexible scale or it can be calculated from the curvature by the formula $\frac{100 \cdot t}{2R}$ where t is the thickness and R the radius to the

neutral plane. The ductility can also be measured by means of a bend extensometer. However, direct measurement is the more satisfactory. For specimens $\frac{1}{4}$ in. or more in thickness, a heavy press or tensile testing machine is desirable.

Root break and side bend tests are new forms of the bend test that have been introduced to reveal lack of soundness in welded joints, but they have not as yet met with general acceptance. The root break test is applied by bending the specimen backward, so as to stretch the bottom of the vee of a single vee weld; it is particularly effective in revealing lack of penetration and soundness at the bottom of the vee. The side bend test is applied by bending a thin specimen taken transversely across the welded joint so that the length of the weld is perpendicular to the plane of the specimen; this test, which is said to be particularly effective

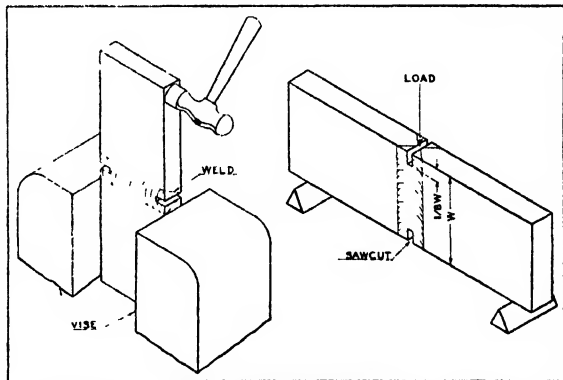


Fig. 10—Nick-break test.

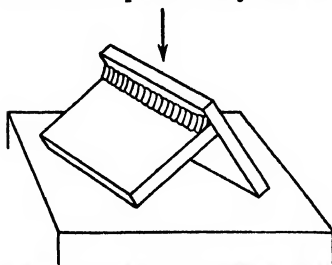


Fig. 11—Test specimen for fillet welds.

in revealing lack of side wall fusion in the vee or groove, is a new one that has been introduced and recommended by the United States Navy Dept., as superior to the widely used nick-break test.

Specific Gravity Test—This test is made to insure freedom from fine porosity and is carried out on a solid cylinder of the weld metal $\frac{1}{8}$ in. dia. x 2 in. long. The weight of the specimen and its volume in metric units are carefully determined, and the weight in grams divided by the volume in cubic centimeters gives the specific gravity. For highest class weld metal a specific gravity of 7.80 is required.

Nick-Break Test—This test consists of rupturing, with a sudden blow, a specimen notched in the weld. It is a homogeneity test and indicates the soundness of the weld by showing on the fractured surface (1) whether complete penetration has been obtained; (2) the presence of oxide or slag inclusions; and (3) the degree of porosity, which should not exceed six gas pockets or holes per square inch of fractured surface. The maximum dimensions of any defect should not exceed $\frac{1}{8}$ in.

The materials required to make the test are a vise or anvil in or against which the specimen is clamped; a heavy hammer for applying the blow, and a specimen whose width is $1\frac{1}{2}t$ plus $\frac{1}{4}$ in., slotted at the edges with a hacksaw for a depth not greater than $\frac{1}{4}$ in. No machining is required on the specimen. With material $\frac{1}{4}$ in. or greater in thickness, the specimen may be laid on supports about 6 in. apart and fractured by a power hammer, or falling weight of sufficient intensity to cause

sudden fracture. Examination of the fractured surface will reveal the presence of porosity, oxide, or lack of fusion.

Although the test is extremely simple, it is severe and only good quality weld metal and welding will pass the test. It constitutes one of the requirements for the qualification of welders in the Am. Soc. Mech. Engrs. Unfired Pressure Vessel Code for Class II Vessels. The specimen is shown in Fig. 10.

For fillet welds, a test equivalent to the nick-break test is applied to a so-called fillet weld break specimen (Fig. 11). This specimen is formed by fillet welding one flat plate or bar at right angle to another, in such a manner that by application of pressure or a blow to one edge of the specimen the fillet weld may be opened up at its root. The resulting fracture in the weld reveals any lack of penetration or soundness.

Impact Tests—The Izod and the Charpy impact tests are generally used. These tests are carried out by fracturing a notched specimen with a swinging pendulum and measuring the energy absorbed in breaking the test piece. The tests are described elsewhere in this Handbook.

It is customary in testing the impact strength of welds to take at least three specimens, placing the notch at the bottom of the weld in one; at the side in another, and at the top in the third, and taking the average of the three results as the impact value in ft-lb.

Hardness Tests—The hardness test is used considerably in the laboratory but has not been used to any great extent in the field for weld testing, except for determining the hardness of built up rail ends. The machines more generally used for hardness testing of welds are the Brinell, Rockwell, and scleroscope. A description of these instruments and the hardness test are given elsewhere in this Handbook.

Stethoscope—The object of the stethoscopic test is to determine by means of the sound a weld gives off when tapped with a hammer, whether the metal is sound or contains defects, such as lack of fusion or cracks. Just as a sound bell gives off a clear ringing note and a cracked bell a reedy note, so good weld metal gives a good ringing sound and a poor weld a flat sound or note.

In order to readily identify the sound an ordinary physician's stethoscope is used, the extra precaution being taken of protecting the end with rubber to avoid any extraneous sounds resulting from scraping the stethoscope on the metal.

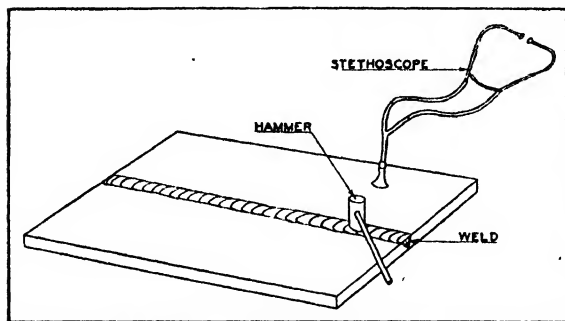


Fig. 12—Stethoscope testing of welds.

The stethoscopic test has been applied successfully to pressure vessels, locomotive staybolts, and welded structures. See Fig. 12.

X-Ray—Metals can be X-rayed and their internal defects made visible on photographic films. In this way all types of defects such as cracks, slag, blowholes, and lack of fusion can be detected. Generally the method consists of placing the X-ray tube on one side and the film on the other of the piece being tested. After an exposure ranging from a

fraction of a minute to fifteen minutes, depending on the power of the tube and the thickness of the metal, the film is developed and examined for defects in the weld.

This method has found wide industrial use and is recognized as the foremost nondestructive test. It is one of the requirements of the Am. Soc. Mech. Engrs. Code for Class I welded pressure vessels.

Gamma Ray Tests—Gamma ray tests are similar in method to X-ray tests. The gamma ray emanating from radium penetrates metals rapidly and is more applicable to heavy sections which would require unusually long exposure by X-rays. It has been successfully applied to heavy castings such as are used in ship construction. On heavy work overnight exposures are employed.

In application several large castings may be arranged radially around a capsula, containing radium at the center. The films for recording the results are placed on

the opposite side of the casting from the radium. Before attempting the use of radium for gamma ray testing, it is essential that the operator be familiar with the properties of radium, and that the necessary precautions be taken to protect those handling it.

Codes and Specifications—Specifications covering construction projects in many fields, are including fusion welding as an acceptable means of fabrication in a majority of cases. On important projects, furthermore, a good many specifications include the manner in which the welding must be carried out and the result which must be obtained. The following extracts and resumes of codes and specifications are given therefore, for the purpose of indicating in general the manner in which various applications of fusion welding are being covered:

A.S.M.E. Boiler Construction Code—The welding rules in the various sections of this Code were initially adopted by the Am. Soc. Mech. Engrs. Boiler Code Committee in 1931. Those in the power boiler section were so drawn as to apply solely to shells and drums and there are no provisions in that section as yet for welding applied to carry stress in furnace construction, water legs, stays, or braces. Those in the heating boiler section permit welding in all parts of the boiler structure without restriction. The welding rules in the unfired pressure vessel section are so drawn as to provide for three definite classes of vessels according to the treatment of the welds and the tests applied. The welding rules in the miniature boiler sections are similar to the so-called Class 2 rules of the Unfired Pressure Vessel Code.

There have recently been added in the unfired pressure vessel section a comprehensive set of rules for vessels subject to external pressure and jacketed vessels which provide for both welded construction and welded attachment of reinforcing rings and flanges. Both the power boiler and the unfired pressure vessel sections have recently been amplified to provide for welded attachment of nozzles, domes, flanges, and flat heads.

Copies of the several sections of this Code may be obtained from the office of the Secretary of the Am. Soc. of Mech. Engrs., 29 West 39th St., New York.

A.P.I.-A.S.M.E. Unfired Pressure Vessel Code—As a result of the exemption in the Am. Soc. Mech. Engrs. Unfired Pressure Vessel Code of vessels for use with petroleum liquids and gases, a joint committee of the two above organizations has recently prepared a specialized pressure vessel code to meet the needs of the petroleum industry. This new Code is worthy of mention as it has been so drawn as to provide adequately for the improved processes and methods of petroleum refining which involve extremely high pressures and temperatures, with attendant rapid corrosion rates. These rules are drawn up at considerable variance with the corresponding rules in the Am. Soc. Mech. Engrs. Unfired Pressure Vessel Code, both as to detail requirements and the scope of construction and repair work covered. Considerably lower factors of safety are here provided for, due to the stringent inspection requirements which form an integral part thereof.

Copies of this Code are available at the office of the Secretary of the Am. Soc. of Mech. Engrs., 29 West 39th St., New York.

U. S. Department of Navigation and Steamboat Inspection—The Marine Boiler Construction Rules of this Federal Department, which has been in existence for nearly sixty years, have recently been revised so as to provide for welded construction and repair of both boilers and pressure vessels. The new Code is divided into two sections, one embracing specifications for the materials and the working stresses allowed, and the other pertaining to the design, construction, installation, inspection, and repair of boiler, pressure vessels, and piping systems; the construction rules of the latter part bear a close similarity to the corresponding rules in the Am. Soc. Mech. Engrs. Boiler Code.

The welding rules in this new Code cover the shells and drums of power boilers, three classes of pressure vessels, and the various types of piping and pipe fittings. The welding rules for this Code are somewhat more stringent and restrictive than the corresponding requirements in the Am. Soc. Mech. Engrs. Boiler Code on account of the particularly hazardous conditions encountered on shipboard. They include the new rules for welded attachment of nozzles, domes, flanges, and flat heads which are incorporated in the Am. Soc. Mech. Engrs. Boiler Code.

Copies of this new Code are obtainable from the office of the Bureau of Navigation and Steamboat Inspection, Department of Commerce, Washington, D. C.

U. S. Navy Department—Specifications for Arc Welding and Specifications for Welded Boiler Drums can be obtained upon application to the Bureau of Engineering, U. S. Navy Department, Washington, D. C.

National Board Rules for Repair of Boilers by Fusion Welding—These rules have been formulated by the National Bureau of Casualty and Surety Underwriters in co-operation with the National Board of Boiler and Pressure Vessel Inspectors, to indicate the extent to which fusion welding is acceptable to the authorities for steam boiler repairs. These rules have been reviewed by the Am. Soc. Mech. Engrs. Boiler Code Committee and pronounced consistent with the power boiler rules in the Am. Soc. Mech. Engrs. Boiler Code. They embrace such applications as welding in staybolted surfaces, welding cracks in circumferential seams of boiler shells, welding cracks in tube ligaments, closure of openings in shells or drums by welded patch plates, safe ending of boiler tubes and welding of cracks and fractures in cast iron heating boilers.

Copies of these rules may be obtained upon application to the National Bureau of Casualty and Surety Underwriters, No. 1 Park Ave., New York.

A.S.A. Pressure Piping Code—The recent issuance of this Code under the sponsorship of the Am. Soc. of Mech. Engrs. has filled a long-felt want in the field of pressure piping. This Code embraces construction requirements for all classes of piping, which include steam and power piping, gas and air piping, oil piping, and piping for district heating purposes. One section is

devoted to fabricating details under which there is a subdivision covering welding and welded fabrication.

Copies of the new Code may be obtained upon application from the office of the Secretary of the Am. Soc. of Mech. Engrs., 29 West 39th St., New York.

Manual of Heating and Piping Contractors' National Association—This is a Handbook covering welded pipe fabrication that has been prepared by this Association for the benefit of architects, consulting engineers, and the piping contractors who are in need of fundamental data on the subject. It contains instructional material for the use of fabricating contractors in training pipe fitters and apprentices to perform welding and is not written in the form of a Code. It contains much important fabricating data and will serve as a valuable guide in both design and construction work.

This Manual can be obtained from the office of the Heating, Piping and Air Conditioning Contractors' National Association, 1250 Sixth Ave., New York.

Rules for Fusion Welding of Gravity Tanks, Tank Risers, and Towers—This is a set of rules that was prepared by a joint committee of the International Acetylene Association and the Am. Welding Soc. to provide for the fusion welding of the above essential parts of sprinkler fire protection systems. This work was undertaken at the specific request of the National Board of Fire Underwriters, which is frequently confronted with the question of welded construction.

Copies of these rules may be obtained upon application to the office of the Secretary of the International Acetylene Association, 30 East 42nd St., New York.

Rules for Welded Construction of Oil Storage Tanks—This is a proposed Code that is receiving the joint consideration of the Am. Welding Soc. and the American Petroleum Institute. It applies to the large above-ground bulk storage tanks that are used by the petroleum companies. The American Petroleum Institute has issued a tentative draft of a proposed Code, but the code under consideration by the Am. Welding Soc. has not as yet been issued.

For information concerning the tentative draft of the American Petroleum Institute application should be made to the office of the Secretary, 50 West 50th St., New York.

Rules for the Fusion Welding of Marine Buoys—This is a Code that has been drafted by the joint activity of the International Acetylene Association and the Am. Welding Soc. for the benefit of the U. S. Bureau of Lighthouses. The scope of the work is to cover not only the plain buoys which require welded shell fabrication but also the light, bell, and whistle buoys which require elements of structural steel work in addition. This Code has not as yet been issued.

A.W.S. Building Code—The latest edition of this Code was issued in 1934 by the Am. Welding Soc. for the guidance of erectors in applying fusion welding and gas cutting.

Information concerning the Code can be obtained upon application to the office of the Secretary of the Am. Welding Soc., 33 West 39th St., New York.

Specification for the Design, Construction, Alteration, and Repair of Railway and Highway Bridges—This Code issued by the Am. Welding Soc., 33 West 39th St., New York, has for its purpose to codify all applications of fusion welding to the construction, maintenance, and repair of steel bridges for both railway and highway usage.

Tentative Code for Fusion Welding and Flame Cutting in Machinery Construction—This Code was issued in 1935 by the Am. Welding Soc. The purpose is to draft rules for machinery construction that will be comparable to those now effective for fusion welding and gas cutting in building construction.

Qualification Tests for Welding Operators—These rules are general in character, having been prepared by the International Acetylene Association to cover the average conditions encountered in welding shop applications and provide for the testing of operators with the least possible time and expense. The tests cover a wide range of materials and types of fabrication.

These rules have been issued in pamphlet form and can be obtained upon application to the office of the Secretary of the International Acetylene Association, 30 East 42nd St., New York.

Specifications for Filler Metal—The Am. Welding Soc. has, after a number of years of study and investigation, adopted as a tentative standard a set of Specifications for Filler Metal to be used in making fusion welded joints. These rules depart from the original thought of requirements pertaining to chemical composition and depend solely on the physical properties that are obtainable therefrom when deposited in the welded joint.

These Specifications were published in the Aug., 1933, issue of the Am. Welding Soc. Journal and can be obtained in pamphlet form upon application to the Secretary of the Am. Welding Soc., 33 West 39th St., New York.

A.S.T.M. Specifications for Steel Suitable for Fusion Welding—In recognition of the remarkable recent advance in the art of fusion welding, the A.S.T.M. has recently issued Specifications A 151-33 to list the classes of steel that are suitable for fusion welding. These Specifications refer to twenty established A.S.T.M. Specifications for rolled plate material, pipe and tubing, and wire which are known to be weldable with satisfactory results under ordinary commercial practices, provided the carbon content does not exceed 0.35%.

Copies of this Specification can be obtained from the office of the Secretary of the A.S.T.M., 260 South Broad St., Philadelphia.

Safe Practices in Fusion Welding—The question of Safe Practices in Fusion Welding is an important one, as there are inherent hazards in certain applications, no matter what the process of welding may be. Special attention will be devoted to the application hazards, as it is not the purpose here to enumerate the safety precautions that must be observed in connection with handling the different welding processes. The latter have been ably and comprehensively covered in the safety pamphlet on Gas and Electric Welding, issued by the National Safety Council as Safe Practices Pamphlet No. 23. This pamphlet embraces much valuable informa-

tion concerning the fundamentals of gas welding and cutting, thermit welding, and electric welding, and it should be consulted by everyone who has charge of fusion welding operations.

In all cases, operators of welding equipment have the advantage of the safe operating instructions that are furnished with all fusion welding equipment and should be conversant therewith. As a rule, welding equipment is so constituted that it is quite convenient to observe the usual precautions for safety, but in the application of the process involved, there are certain conditions and operations that may endanger the operator if the possibility is not anticipated and avoided. Some of these hazards will be enumerated.

Eye Protection—An important hazard in welding applications is that of injury to the eyes, from the heat and glare of the flame or arc, and from particles of hot metal that may fly up from the work. Properly colored lenses fitted in goggles will protect the eyes from the gas flame, but in the case of electric arc welding the intensity of the ultra-violet and infra-red rays is such that it is necessary for all persons exposed to use shields or helmets that will protect not only the eyes but the skin also. In the case of goggles, the lens should be selected with considerable care in order to obtain the desired visibility together with adequate eye protection; the exterior surfaces of these lenses may be to advantage protected from flying sparks by superimposing a clear glass lens over each. In the case of lens for use with the electric arc, the selection must be based on laboratory tests, as their transmission of ultra-violet and infra-red radiation cannot be determined by visual inspection; proper eye protection requires more than mere reduction of the glare. Goggle frames should be of noncombustible material and preferably a nonconductor of heat; if of metal they should be padded. The frames should have vent holes in the cups to provide ventilation back of the lenses.

Special precautions must be taken to protect other workers or passers-by from the harmful rays given off from arc welding operations. It is preferable to locate these jobs in special rooms. If this is impracticable, the operations should be screened or enclosed not only to prevent workers or passers-by from looking directly at the arc, but also to protect them from reflected rays as much as possible. Further protection against reflected rays is frequently provided by applying paint to the screen or enclosure and to other nearby surfaces. Zinc oxide combined with lamp black to produce a bluish gray color is satisfactory.

Clothing—The welding operator should have some protection from the heat of welding, particularly when working on heavy work and for long periods of time. In such case fire-resisting gauntlet gloves and aprons will serve as a protection against the radiated heat. Woollen clothing is to be preferred to cotton, as it is not so readily ignited and it protects the operator from changes in temperature. It is recommended that operators on arc welding wear only fireproofed outer clothing.

There have been instances when the operator's clothing has been set on fire by sparks of molten metal which lodge in rolled-up sleeves, and in pockets of clothing. Operators should be warned to keep sleeves buttoned around the wrist and their collars buttoned to prevent lodgment of sparks. Some suggest that it is advisable to eliminate pockets in front of overalls and aprons. A sheet iron screen in front of the worker's legs will provide further protection against sparks and molten metal in gas cutting.

Electric Installation—When installing and operating electric equipment, the provisions of the National Electrical Safety Code should be followed. The voltage is in most cases so low that there is little danger from shock from the welding circuit, but still the usual precautions should be taken. There are, however, some types of equipment that have a high voltage under open circuit conditions and these should be properly guarded.

Fire Protection—Where welding or cutting has to be done in the vicinity of combustible material, special precautions should be taken to make certain that sparks or hot slag from the welding or cutting operations do not reach combustible material and thus start a fire.

Cutting or welding work which can be transported should be removed to a safe location in a sprinklered or noncombustible building. If the work cannot be moved, exposed combustible material should if possible be moved a safe distance away, say 30 or 40 ft. Wherever there are floor openings or cracks in the flooring, it is also advisable to make certain that there are no highly combustible materials

on the floor below, where they would be exposed to sparks which might drop through the floor.

The sparks and hot slag should be watched to see that they do not come in contact with combustible material, do not lodge in floor cracks, and do not drop through holes to the floor below. Sheet metal guards or asbestos curtains should be used where needed; make sure that the guards and curtains are adequate. Because hot slag may roll along the floor for considerable distance, it is important when using asbestos blankets as a curtain that no openings exist where the curtain meets the floor. Avoid the use of tarpaulins as experience has shown that they do not provide adequate protection.

Extra men should be stationed with small hose, chemical extinguishers, or fire pails nearby when the nature of the work requires that blowpipes be used near wooden construction or in locations where the combustible material cannot be removed. In sprinklered buildings, maintain sprinkler protection without interruption while cutting blowpipes are being used. A man should be kept at the scene of the work for a half hour after completion to make sure that sparks have not started smoldering fires.

Dusty and gassy atmospheres in certain mines, mills, industrial plants, and plants spraying lacquers and the like require extra precautions to avoid explosions or fires from electric sparks, matches, and open fires. Welding or cutting in such suspicious places should therefore be done only when proper precautions have been taken and only after the responsible official in charge has inspected the situation and has personally given instructions to proceed.

Ventilation—When working in a confined space, be sure of proper and adequate ventilation, by natural means or by an air fan or blower. Oxygen should never be fed from a cylinder into a confined space as it is unsafe to do so. Welding or cutting in confined spaces is a job requiring special precautions. The operator should wear special clothing—preferably fireproofed, but certainly of wool.

When the operator is working in a confined space, always have a helper present outside of the confined space to close the cylinder valves or help in other cases of emergency. All equipment should be tested for leaks before taking it into such places, and when work is interrupted for any reason it should be brought out.

Welding on brass, bronze, or galvanized iron should be conducted in well ventilated locations and operators should be supplied with suitable respirators to prevent the inhalation of zinc fumes, particularly if the welding job is of any considerable duration. In the event of the workman experiencing any nausea after he has been welding brass, bronze, or galvanized iron, he should drink milk copiously. Where flame cutting has to be done on metal that has been surface coated with lead paint, the operator should be provided with a gas mask which will supply him fresh air uncontaminated with lead fumes.

Special Precautions—No welding or cutting should be done on used drums, barrels, tanks, or other containers until they have been cleaned so thoroughly as to make absolutely certain that no flammable materials are present. Where steam is available, this may be used to remove materials which are easily volatile. Washing with strong caustic soda solution will remove heavier oils. Even after thorough cleansing, the container should wherever possible be filled with water before any welding, cutting, or other hot work operation is performed. In practically every case it will be found possible to place the container in such a position that it can be kept filled with water to within a few inches of the point where welding or cutting is to be done. In doing this, care should be taken to make sure that there is a vent or opening to provide for the release of heated air from inside the container. This can usually be done by opening the bung, hand hole, or other fitting which is above the water level.

Where alterations or repairs are being carried out on large containers that have held flammable substances, periodic examination of the air contents of the vessels should be made from time to time wherever possible, by means of a gas detector where such an instrument is available. Although the vessel may have been steamed and flushed with soda there may still be traces of oil or grease under seams and the heat of the welding or cutting operations may cause such oil or grease to give off flammable vapor to the extent that an explosive mixture may be formed inside of the tank. If possible, keep a supply of carbon dioxide in the vessels while under the process of repair. The use of carbon tetrachloride for this

purpose is not recommended as carbon tetrachloride gives off a poisonous vapor when heated.

A jacketed vessel, tank or container should never be welded until after every possible precaution has been taken to vent the confined air sufficiently. A metal part which is suspiciously light is hollow inside, and should be drilled before heating. Otherwise it will act like a bomb.

Gas cutting should be used with judgment and care as to the effect upon the structure. No important structural member should be cut while it is under load, except where the removal of the part will not reduce the strength of the part. Also great caution should be used in cutting holes in or removing portions from structural members unless the design provides therefor without weakening. If gas cutting is used to remove rivets, great care should be used in removing the head, to avoid reducing the thickness of the base metal at the rivet hole. In cutting away any important or heavy member of a machine or structure, caution should be exercised to make sure that the severed part will not fall and cause damage to adjacent equipment. If the part is likely to fall and injure the operator or other workmen, care should be taken to properly support it while it is being cut. One of the common errors in cutting is to allow a part to fall on the operator's feet.

Health Protection—If painted or lead coated materials are cut or welded, the lead volatilizes and may be breathed into the operator's lungs, causing lead poisoning. In a similar way "zinc chills" may result from breathing the fumes when welding zinc, brass, bronze, or galvanized metal.

Under such conditions, ventilation must be depended on to protect the operators; or better yet, the operators should be required to wear special gas masks or fresh air masks.

Special care must be exercised when welding or cutting operations are carried on in confined and poorly ventilated spaces, such as in tanks, compartments, and holds of vessels. Artificial ventilation may be necessary to replace the oxygen consumed from the air and the operators should be under close observation by an outside attendant so help can be rendered immediately in an emergency.

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Industrial Heating Furnaces

By M. H. Mawhinney*

Introduction—This article covers the electric and fuel fired furnaces for heat treating purposes, operating at all temperatures up to about 2400°F. It does not include melting furnaces, or electric furnaces of the arc type or the induction type.

Principles of Combustion—The combustion of fuel (solid, liquid, or gaseous) consists of the rapid oxidation of the combustible portion of the fuel to produce heat. The theoretical heat energy available depends upon the net calorific value of the combustible content, and the temperature produced depends upon the nature of the gaseous products to be heated by this available heat energy. When the combustible elements (usually C and H₂) are combined with the theoretically correct amount of air, the resulting products of combustion are confined to CO₂ and N₂ from the air, and water vapor. Excess O₂ in the flue gases serves as a measure of the air-fuel mixture on the lean side (too much air) and CO in the flue gases indicates the richness (too much fuel) of the fuel mixture.

Fuels are generally sold on the basis of the higher heating value in B.t.u., which is the gross chemical energy, while the net useful energy is the lower heating value, after the heat necessary to convert the water in the flue gases to vapor has been subtracted.

For most fuels (exclusive of producer gas and blast furnace gas) the amount of air required for combustion is about 1 cu.ft. for each 100 B.t.u. of lower heating value. Table I shows the physical characteristics of the principal fuels used in heating furnaces.

Fuels for Heat Treating—Where metallurgical requirements are rigid the most suitable combustible fuels are natural gas, liquefied petroleum gas, artificial gas, and oil. Of these fuels, the gases are the most satisfactory for temperature control and the maintenance of the proper atmosphere in the furnace, but equally good results are obtained with oil by care in furnace design and careful supervision of operation.

For rougher forms of heating (forging, forming, and rolling) the remaining fuels may be utilized, although the specifications on this class of heating are becoming more exacting, and considerable care and supervision is required to meet the requirements with fuels which do not lend themselves to consistently automatic control.

Methods of Heat Application—Methods of firing furnaces heated with combustible fuels include:

1. Recirculation system is used for low temperatures (usually under 1100°F.) where gas or oil is burned in a separate chamber and the resulting products of combustion are circulated through the furnace by a fan.
2. Indirect firing is used for all temperatures up to 1900°F., where combustion chambers are located below (underfired), at the side of (side fired), or above (overfired) the heating charge, and separated from the heating chamber by suitable baffles. (While indirect firing is more common at temperatures below 1900°F. it is possible to design a gas fired furnace so that it will operate satisfactorily from 1000–1900°F. and still have the firing direct into the furnace oven.)
3. Direct fired is used for temperatures above 1900°F. where the burners fire directly into the heating chamber, usually above the charge.

Burner Systems for Heating Furnaces—The various types of burners commonly used on heating furnaces are given in Table II.

The use of stacks in connection with heating furnaces is being gradually discontinued, because modern burners do not require stack draft, and because the usual failure to control the draft by proper damper operation results in large quantities of excess air in the furnace at low fuel rates.

Types of Electric Furnaces—Electric furnaces (resistor type is here considered) are ordinarily limited to those applications for which temperatures do not exceed 1900°F., because the life of the metal resistor elements is uneconomical above that temperature. Exceptions are the furnaces employing carbon resistor elements in granulated and bar forms at temperatures up to 2300°F., and furnaces containing protective atmospheres which have been successfully operated with metallic heating elements at 2100°F. for brazing.

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Table I
Properties of Fuels*

Fuel	Average Chemical Analysis by Weight for Solids and Liquids; Volume for Gases											Lower Heating Value B.t.u. per Unit of Fuel**	Density Lb. per Unit Conditions	Cold Combustion Air, Cuft. per Unit Perfect Combustion	Cold Flue Gases Cuft. per Unit	Density of Flue Gases Lb. per Cuft.	
	S	H ₂	C	N ₂	O ₂	CH ₄	C ₂ H ₆	CO	CO ₂	Humid-nants	Ash						C ₂ H ₄
	Liquids: Volume for Gases																
Lignite	0.9	6.8	41.3	0.7	40.7	...	...	...	...	...	9.6	...	7,189	40	71	82	0.0760
Subbituminous coal	0.6	5.9	60.1	1.0	27.0	...	...	...	...	...	5.4	...	10,587	To	103	112	0.0782
Bituminous coal	0.5	5.2	78.0	1.3	11.5	...	...	...	...	...	3.4	...	14,134	50	137	143	0.0790
Semibituminous coal	0.5	4.8	84.6	1.0	5.1	...	...	...	...	...	4.0	...	14,689	Lb./Cuft. Piled	148	153	0.0795
Cannel coal	1.0	6.8	73.3	1.3	8.3	...	...	...	...	...	9.3	...	14,251	7.55	139	146	0.0782
Fuel oil, 24° Be.	...	13.0	83.7	2.0	1.3	...	...	...	...	...	...	...	140,000	9.49	1410	1505	0.0760
Coal tar	0.8	6.0	86.7	0.1	3.0	...	...	...	...	...	0.1	...	150,000	9.49	1500	1560	0.0785
Natural gas (Ohio)	...	...	...	5.0	...	80.3	14.7	...	...	...	...	...	970	0.0491	10.11	11.19	0.0730
Coke oven gas	...	53.0	...	12.1	...	28.1	...	6.0	0.8	...	...	...	425	0.0288	4.08	4.79	0.0708
Blast furnace gas	...	...	...	65.0	0.1	...	...	27.8	7.1	...	...	...	90	0.0767	0.68	1.52	0.0830
Raw producer gas	...	12.5	...	56.5	...	3.0	...	20.5	7.5	...	...	...	138	0.0674	1.07	1.91	0.0780
Clean producer gas	...	13.5	...	54.8	...	3.0	...	19.0	9.7	...	...	...	128	0.0677	1.06	1.90	0.0780
Coal gas	...	47.0	...	2.3	...	34.0	...	9.0	1.1	...	...	6.6	569	0.0313	5.51	6.23	0.0715
Blue water gas	...	52.9	...	4.7	...	2.2	...	36.8	...	3.4	...	...	287	0.0342	2.35	2.87	0.0740
Carburetted water gas	...	35.2	...	1.8	...	14.8	...	33.9	1.5	...	12.8	...	535	0.0454	4.88	5.54	0.0750
Oil gas	...	58.4	...	3.8	...	28.8	...	4.4	1.2	3.4	...	...	440	0.0226	4.23	4.88	0.0705
Butane gas	C ₄ H ₁₀	3,020	0.1526	31.00	33.60	0.0750
Propane gas	C ₃ H ₈	2,322	0.1158	23.80	25.80	0.0745

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**Units are lb. for coals, gal. for oil and tar, and cuft. for gases.

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The metallic heating elements commonly used are of heat resisting alloy in either rolled or cast form. In the rolled form the alloy wire or flat strip is looped on refractory or metal hangers to form a radiating grid on the sidewalls, roof, or bottom of the furnace. The cast alloy is cast in grids made up of similar loops of various cross sections, and the grid hung or supported on hangers and guides provided in the refractory lining of the furnace.

The disposition of the heating elements in the furnace is one of the principal considerations in the uniform transfer of heat to the heating charge. At the usual heat treating temperatures, from 85-95% of the heat in a furnace (electric or fuel fired) is transferred by radiation (the remainder by convection) and the radiating elements must be placed with consideration of the heat requirements. It is for this reason that more element area is provided adjacent to doors and other openings, where the heat requirement is relatively great.

Table II
Burners for Heat Treating Furnaces

Fuel	Designation	Approximate Pressure/Sq. in. Air		Comments
		Fuel	Air	
Oil and tar	Steam atomizing	10-40 lb.	¼-4 oz.	Steam at 60 lb. min. 40-50% induced air
	Low pressure	10-40 lb.	8-16 oz.	
Producer gas	Mixing type	2 in. water	4 oz.-5 lb.	Scrapers or steam jets for cleaning tar and soot
Blast furnace gas	Proportioning	3 oz.	8-16 oz.	Automatic air-gas mixing
Natural and artificial clean gases	Blast type, or nozzle mixing	4-8 oz.	3-16 oz.	{ Separate air and gas control, automatic mixing, all air inspired. Highly luminous flame
	Proportioning	3 oz.	8-16 oz.	
	High Pressure	10-25 lb.	Atmosphere	
	Luminous or radiant	3-8 oz.	3-8 oz.	

Characteristics of Electric Heat—Electric heat offers the following principal advantages over furnaces heated by the combustion of fuel:

1. Quietness and cleanliness of operation.
2. Consistency of operation and freedom from personal element resulting from adjustment of fuel. After initial adjustment, the electric furnace requires no further regulation of heat input.
3. Uniformity of temperature in those applications for which electric heat is applicable (certain applications, such as large masses and rough heating at high rates, are difficult with radiant electric heat).
4. Use of protective atmospheres without the necessity for muffles.

The principal disadvantages, in comparison with fuel fired furnaces are: (1) High B.t.u. cost of electricity; (2) less flexibility of adjustment where heat requirements fluctuate rapidly; and (3) slow heating up from a cold condition.

Design Data—It has been mentioned that the location of the elements is important in obtaining uniform furnace temperatures. Of equal importance is the current density carried on the elements. If the element area is too small, with consequent high release of energy in watts per square inch of element, the element temperature will exceed the furnace temperature to such an extent that local overheating of the charge adjacent to elements must result. This is particularly true at low temperatures of about 1000°F., where for best uniformity the energy liberation must be kept down to from 6-8 watts per sq. in. As the temperature is increased, higher rates are permissible, so that at 1500°F. the rate may be 10-12 watts per sq. in. Beyond 1500°F. the rate must again decrease on account of element failure, and at 2000°F., the rate of liberation should not exceed 8 watts per sq. in.

Where possible, electric furnaces are connected across the line which saves the expense of transformers, but frequently the elements based on line voltage are too light for satisfactory life and transformers are necessary.

Muffles—Where a perfectly consistent atmosphere must be maintained (as for bright annealing of metals), the leakage through joints prevents the use of refractory muffles, so metal muffles of heat resisting alloy (cast or rolled forms) must be used. The construction and maintenance of such muffles in any size is a mechanical problem involving a great many difficulties from warpage, due to uneven expansion and contraction.

The use of muffles decreases the heating capacity of a furnace about 20%, as compared to an open furnace, and the fuel consumption is increased by the necessity for higher temperatures outside the muffle and consequently greater radiation losses.

Pot Furnaces—Pot furnaces are frequently used in heat treating, and although costly and troublesome because of the necessity for pot replacement and losses of liquid heating medium, they have the advantages of no oxidation of heated materials, rapid and uniform heating, and ability to treat only a portion of a piece without affecting the remainder. Heat treating salts and lead are commonly used as the heating media.

The capacity of a salt pot for operation at 1500°F. in lb. of steel heated per hour is about 3/10 times the weight of salt in the pot. The usual consumption of lead is about ½ lb. per 100 lb. of steel treated and about 1 lb. of charcoal is used per hour for covering each square foot of lead bath. The average consumption of salts is about ½ lb. per 100 lb. steel at 1200°F. average bath temperature and about 7/10 lb. at 1500°F.

Material Handling in Furnaces—The selection of the best method of handling material through furnaces involves difficult problems. The following rules should always be followed:

1. A furnace is a heat treating machine and the method of conveying the material must not compromise the heating characteristics of the furnace.
2. The advantages of simplicity in design of hot conveyors should not be overlooked in a desire to save labor.
3. In the selection of conveying means, those which will damage the material under consideration must first be eliminated. Examples are the scratching of nonferrous metals, damage to threaded parts, sagging and denting of tubular products. Conveying means which interfere with the circulation of heat where precision of heat treatment is necessary, must also be eliminated.

The various methods of handling for industrial heating include:

Batch—The batch methods consist of the stationary hearth, solid bottom; stationary hearth, roller bottom; car bottom; and removable furnace covers and pits.

Semicontinuous—The semicontinuous method consists of a stationary hearth or car bottom furnaces in conjunction with handling forks or special cranes to reduce the time between charges to several minutes.

Continuous—The continuous methods consist of the pusher, direct or on pans or shoes; tunnel kilns, with cars; chain conveyor and moving fingers; walking beam; roller hearth; rotary hearth; rotating retorts; and miscellaneous special types.

Furnace Materials—For estimating comparative operating costs of different designs, it is safe to assume that firebrick linings will last for 2 yr. at temperatures below 1900°F., and for 1 yr. above 2000°F. This does not apply to door jambs, piers and bridgewalls, which will require additional patching. The life of metal parts when properly designed for stress, and for usual furnace conditions will be approximately as follows:

		Cast Iron	Alloy
Below 1400°F.	.....	5 years	
1700°F.	.....	12 months	3 years
1800°F.	.....	5 months	2 years
1900°F.	.....	1 month	1½ years
2000°F.	.....	not used	½ year

Commonly used alloy analyses in the design of furnace parts include:

Furnace Temp., Below 1400°F.		Furnace Temp., Above 1400°F.	
Nickel, %	Chromium, %	Nickel, %	Chromium, %
25	20	68	18
18	8	60	12
8	18	38	18
..	28	35	15
..	18	30	10
		12	28
		11	25

Determination of Furnace Size*—The size of furnace required depends upon the amount of material to be heated per hour, the heating time required, the size of the pieces to be heated, and the amount of heat which can be liberated without excessive damage to the furnace. The efficiency and refractory life obtained, depend upon the correctness of the furnace size.

The heating time in the furnace depends upon the nature of the heating process. For the simple case of thorough heating, the time required may be estimated from such rules as 5 min. for each $\frac{1}{8}$ in. of thickness of flat plates of steel (heated from one side) and 20 min. per in. of diameter or round steel bars. These rules apply when the furnace temperature is above 1400°F. At 800°F. the time is increased about 100%, and below 800°F., it may require as much as three times as long to heat thoroughly as it does above 1400°F. The time required for heating varies also with the material to be heated. Brass requires about one-half as long as steel to heat and copper 40% as long. The above rules represent the minimum time in which the material will conduct heat to its interior and therefore, will not be greatly affected by variations in the difference between the furnace temperature and that of the material. The rules also assume that the material is fully exposed to the heat of the furnace. Piling of material in a furnace lengthens the heating time, which cannot be expressed numerically, but must be determined by actual trial. In addition to simple heating, there is frequently additional time required for holding at temperature.

The weight of material in the furnace at any time is the product of weight of material discharged per hour, multiplied by the heating time in hours. Knowing the weight and sizes of pieces involved, the area of the furnace can then be fixed. The width and length of the furnace to produce this hearth area are fixed by the method of firing to be used and by the method of handling material.

The life of a furnace at a given temperature depends upon the rate of heating, which may be expressed in pounds per square foot of hearth area per hour. The maximum allowable rate of heating steel is about 35 lb. per sq. ft. per hr. for underfired and overfired furnaces, 70 lb. for sidefired furnaces, and 100 lb. for direct fired furnaces. These are upper limits which should not be exceeded if long life of the furnace refractories is expected. The above rates are for heating mild steel, and may be about twice as great when heating brass, $2\frac{1}{2}$ times as great for copper, and 0.7 times as great for alloy steels. These maximum allowable rates should be used only for checking the calculation of size, because some shapes and sizes of pieces cannot be properly heated when piled in such a manner as to produce these rates.

Calculating Furnace Size—If a furnace is required to heat 20 pieces per hour weighing 30 lb. each and requiring a heating time of $\frac{1}{2}$ hr., the furnace must be large enough to hold $\frac{1}{2} \times 20 = 10$ pieces. If each piece requires an area of 2 sq. ft., the area of the hearth will be $2 \times 10 = 20$ sq. ft. for a single layer of pieces in the furnace. If the furnace is of the batch type, a size of 4 ft. wide x 5 ft. deep would probably be about right for convenient handling. Checking the rate of heating (20 pieces per hr. x 30 lb.) per 20 sq. ft. = 30 lb. per sq. ft. per hr. For this rate, an underfired furnace would be satisfactory, while for other methods of firing a smaller furnace could be used, if the pieces could be more densely piled without seriously interfering with the circulation in the furnace.

The allowable rate of heating, expressed in pounds of steel per square foot of hearth area per hour, varies according to temperature. At tempering temperatures of about 1000°F., the usual rate is about 25 lb. per sq. ft. per hr., compared to the allowable rate of 30 lb., given above for heat treating at 1500-1600°F. By means of fans for air circulation, this rate may be increased to 35 lb. in an electric furnace. At heat treating temperatures of 1500-1600°F., air circulation will not increase the rate of heating sufficiently to be worth while, because the amount of heat transferred by convection is small.

Economy of Furnaces—The heat input to a heating furnace is distributed in various ways, depending upon the type of furnace. Ordinarily, the heat balance includes useful heat to material; heat to conveyors, shoes, or pans; radiation and absorption to the furnace lining; radiation through openings; sensible heat in waste

*From, Combustion Furnace Section, by M. H. Mawhinney, Mark's Mechanical Engineers' Handbook, Third Edition, McGraw-Hill Co.

gases of fuel furnaces; and heat in unburned fuel in waste gases of fuel fired furnaces. Miscellaneous additional items include heat to water cooled parts, radiation from cars in car bottom furnaces when the car is out of the furnace, or conduction by metal parts extending out of a furnace.*

It is quite customary to line electric furnaces with a greater quantity of insulation than is used in fuel fired furnaces, on account of the higher cost of electric current per heat unit. However, because of the absence of waste gases in electric furnaces, this smaller amount of radiation appears as a greater per cent of the heat input.

Table III gives the average fuel economies for typical heating furnaces, expressed in B.t.u. per lb. of material heated in fuel furnaces, and in kw-hr. per ton for electric furnaces. The values given represent good operation at efficient rates of production, and are for operation without recuperators or other heat saving devices. To obtain the fuel consumption, divide the economy in B.t.u. per lb. by the lower heating value of the fuel under consideration from Table I. The values of Table III are typical figures and will vary for different furnaces.

Table III
Fuel Economies for Heating Furnaces

Operation	Average Temp., °F.	Average Economy Good Operation	
		Fuel B.t.u. per lb.	Electric kw-hr. per ton
Tempering—Batch type	1000	700	120
Chain conveyor	1000	500	110
Hardening, annealing, normalizing.....	1500-1700		
Batch type		1250	300
Rotary hearth		850	210
Pusher, direct		900	225
Pusher, pans		1400	340
Chain conveyor		1000	245
Car type		1200	290
Roller hearth, steel sheet.....		850	...
Box anneal, sheets.....		1300	...
Carburizing in boxes.....	1650		
Batch type		1500*	400*
Pusher, straight		1200*	325*
Pusher, counterflow recuperative.....		750*	150*
Enameling:			
Batch, sanitary 3 coats.....	1750	2150	...
Continuous, flat ware.....	1500-1650		
Ground coat		2500	320
Finish coat		1750	220
Lead pots	1500	1500	225
Heating for forming.....	1900		
Batch		1750	...
Continuous pusher		1600	...
Plate reheating	1800	1800	...
Forging:	2200		
Batch		2800	500
Continuous, pusher		1400	...
Rotary hearth		1600	...
Wire patenting	1850	1500	...
Heating for rolling.....	2400		
Batch, 4-6 doors.....		1800	...
Continuous pusher		900	...
Soaking pits for hot ingots.....	2400	600	...
Copper billet heating.....	1700	500	...
Annealing brass and copper.....	1000-1200		
Pan type batch.....		400	...
Continuous, pans		350	110
Continuous, chain		350	110
Continuous, counterflow		160	50
Heat treating aluminum:			
Continuous, forging	880	...	140
Pit type—21 hr. heating.....	960	...	265
Car type	975	...	200

*Economies for carburizing furnaces are fuel per gross weight, including boxes and compound. The values will vary with depth of case.

*The method of calculating these various losses may be found in *Industrial Heating Furnaces*, by W. Trinks, and *Practical Industrial Furnace Design*, by M. H. Mawhinney, both published by John Wiley & Sons, Inc.

Furnace Atmospheres—The knowledge of this subject is at present in a stage of such rapid evolution, that it is difficult to express definite conclusions without fear of contradiction. Interest in the possibilities of atmosphere control for reduction and elimination of scale oxidation has been awakened by a recent flood of discoveries. This research has included, principally, the action of the several constituents of combustion gases on hot steel and methods of bright heating of ferrous and nonferrous metals without oxidation by the use of specially prepared gases introduced into electric or muffle furnaces. Several years will be required to digest and assort the amount of data recently published on these subjects.

Atmosphere in Fuel Furnaces—It has been generally understood for many years that the principal constituents of combustion gases are CO_2 , nitrogen, water vapor, and CO or O_2 . The proportions depend upon the degree of mixing and the relative quantities of fuel and air introduced into the burners. Several simultaneous publications in 1930 brought to general notice the fact that H_2 also exists in flue gases in quantity about equal to that of the CO content.

Since that time, extensive research has been carried on to determine the effects of furnace atmospheres, and a summary of the principal conclusions can be found under the heading "Furnace Atmospheres and Steel," by Clair Upthegrove in the American Gas Association Monthly for May, 1933.

In general, it has been found that the scaling, or oxidizing gases in a furnace atmosphere are CO_2 , water vapor, and O_2 , while the reducing constituents are CO, H_2 , and unburned hydrocarbons from the fuel. The scaling action of the atmosphere at any temperature and for any time of contact depends upon the relative proportions of these gases in the atmosphere. The so-called neutral atmosphere, where theoretically correct quantity of air is introduced with the fuel, resulting in a complete absence of O_2 or CO in the atmosphere, is a scaling atmosphere because the proportions of CO_2 and water vapor are high. To reduce the scaling of carbon steel to 50% of that resulting with this atmosphere, requires the excess of fuel necessary to give about 2% CO in the flue gases at 1700°F ., and about 14% CO at 2300°F . To eliminate scale in a combustion furnace is practically impossible. Sulphur in the fuel also increases the amount of scaling of steel.

In addition to scaling, the atmospheres of fuel furnaces frequently decarburize. Moist H_2 and water vapor are principally responsible, and where decarburization must be avoided, an oxidizing furnace atmosphere, with excess air, is the best method. Such an atmosphere is lower in CO_2 content, and in addition, the scale caused by such an atmosphere will inhibit decarburization.

Atmosphere in Electric or Muffle Furnaces—The atmosphere in these furnaces is normally air from the atmosphere which forms a heavy free scale on steel at all temperatures above about 1200°F ., the amount of scale depending upon the temperature.

So far it has been found impractical to operate direct fired fuel furnaces with sufficient CO and H_2 content to offset the scaling action of water vapor and CO_2 , so the developments in bright heating have been confined to electric and muffle furnaces. This is accomplished by maintaining a truly neutral atmosphere in the furnace or muffle, so that no oxidizing reaction between steel and atmosphere takes place. Such atmospheres include H_2 from electrolytic dissociation of water, dissociated ammonia, and mixed gases obtained from partial combustion of hydrocarbon gases. By the use of specially prepared gases, the carbon content of the steel can also be controlled.

Automatic Control of Atmosphere—The automatic control of atmosphere in fuel furnaces involves the control of fuel-air ratio and the control of furnace pressure. The methods of fuel-air control commonly used for fuel fired heat treating furnaces include the following:

1. The method of manual adjustment of fuel and air valves for high and low settings is used for two pipe burner systems, oil or gas fuel, and with two position control.
2. Proportioning valves depend upon constant ratio of fuel and air orifices at all settings and are used for two pipe burner systems, oil or gas, with two or three position and proportioning (multiposition) control.
3. High pressure gas burners or injectors, where gas automatically injects a constant ratio of air and flow of gas only is controlled; used with all kinds of control.
4. Low pressure proportioning systems for gas, where gas is reduced to zero pressure and air automatically inspirates a constant ratio of gas and flow of air only is controlled; used with all kinds of control.

With fixed fuel-air ratio, automatic pressure control is necessary to maintain constant furnace atmosphere on account of the variation of fuel rates. Unless a constant pressure is maintained at all times in the furnace, air will enter the furnace and cause an oxidizing condition. The pressure is a function of the openings in the furnace and the fuel rate. Therefore, to maintain pressure, the openings must automatically adjust themselves to the rate of fuel flow.

Comparative Costs of Fuels—In comparing the cost of operation, the major items for consideration are: 1. Charges on the investment; 2. labor; 3. maintenance; and 4. fuel. The first three items depend largely upon the construction of the furnace and the type of conveyor or other mechanism involved for handling. A true comparison of fuel cost must include a consideration of the percentage of heat lost in the flue gases. For example, all of the heat liberated in an electric furnace at all temperatures goes to heating the metal, the furnace lining, radiation through openings, and such losses. In contrast, a fuel fired furnace involves an additional loss in the flue gases leaving the furnace.

Table IV gives the amounts of various fuels which equal 1 kw-hr. of electric heat at different temperatures, after correcting for flue gas losses. The comparative cost is also shown in the table based on assumed fuel costs which are given. The B.t.u. equivalent of 1 kw-hr. used in this table is 3415.

Table IV
Comparison of Fuels

	Furnace Temp., °F.	Net B.t.u. per Unit	Cost per Unit, Cents	Units Equivalent to 1 kw-hr.	Cost Equivalent to 1 kw-hr. Cents
Electricity	all	3415	1.0	1.0	1.0
Bituminous coal, lb.....	1000	14000	0.26	0.294	0.074
	1500			0.338	0.085
	2000			0.397	0.100
Fuel oil, gal.....	1000	140000	5.0	0.029	0.145
	1500			0.034	0.170
	2000			0.040	0.200
Natural gas, cu.ft.....	1000	1020	0.04	4.03	0.161
	1500			4.63	0.185
	2000			5.45	0.218
Artificial gas, cu.ft.....	1000	475	0.08	8.65	0.692
	1500			9.96	0.798
	2000			11.70	0.935
Butane, cu.ft.	1000	3020	0.19	1.38	0.262
	1500			1.59	0.302
	2000			1.87	0.355
Coke oven gas, cu.ft.....	1000	510	0.01	8.06	0.081
	1500			9.26	0.093
	2000			10.90	0.109
Producer gas, cu.ft.....	1000	150	0.003	30.3	0.091
	1500			37.3	0.112
	2000			46.9	0.141
Blast furnace gas, cu.ft.....	1000	90	0.0023	57.0	0.131
	1500			79.4	0.183
	2000			126.5	0.290

The figures in Table IV afford a comparison of the cost of heating with various fuels, assuming the same furnace construction in all cases. In actual practice, more insulation is used on electric furnaces than on fuel furnaces, so that the relative cost of electricity with respect to other fuels is slightly less than is indicated by the table.

The cost of fuels is a guide in their selection, but should never be used alone to determine the best fuel for any given conditions. The relative convenience and cost of preparation must be carefully studied. Of even more importance is the kind of heating possible with various fuels, including accuracy of control, and nature of surface obtainable. The fundamental purpose of a furnace is to properly heat a given material, and frequently the savings from the use of a cheap fuel are quickly lost in the cost of material spoiled by improper heating.

Fuel to Heat Cold Furnace—It is often desirable to know the quantity of fuel required to heat a furnace from cold to operating temperature. This may be calculated from the data in Table V. These values are based on the usual practice

of firing hard at the start and cutting down the fuel rate as the furnace comes up to temperature.

Table V

Rate of heat liberation (B.t.u. fired per sq. ft. of interior per hr.) required to heat firebrick lined furnace to temperature in given time.

Hours to Final Temp., Ready for Operation	Operating Temp., °F.		
	1000	1500	2000
2	6000	12000	....
4	4200	6800	13500
6	3300	5100	8000
8	2700	4300	6000
10	2200	3800	5200
12	1800	3300	4800
14	1600	3000	4500

Furnaces lined with the so-called "light refractories", which are made to combine a part of the advantages of both firebrick and insulating brick, will heat up in about one-half the time required for firebrick, with the same rate of heat input.

The following illustrates the use of Table V for calculating the quantity of fuel oil required to heat a firebrick furnace with 1000 sq. ft. interior area, from cold to 1500°F. in 4 hr.

$$\frac{4 \text{ hr.} \times 6800 \times 1000}{140,000 \text{ B.t.u. / gal.}} = 194 \text{ gal. oil}$$

Operation of Oil and Gas Burners—There are several fundamental facts which should be kept clearly in mind when lighting furnaces equipped with oil or gas burners. For all fuel fired furnaces, observe the following rules:

1. Open all doors before lighting the furnace.
2. When lighting oil burners or gas burners of the blast (two pipe) type, turn the air on first, then the fuel.
3. When lighting gas burners of the low pressure proportional mixing type, always open the gas supply valve wide; all regulation of fuel is by the air flow and the ratio adjusting screw on the mixer.
4. When shutting off an oil burner, or a gas burner of any type, always shut off the fuel first.

Due to the rapid ignition of most gaseous fuels, there is generally little difficulty in keeping gas burners lighted. With oil burners, however, care must be taken when lighting. When the finely divided atomized oil strikes cold surfaces in the furnace, condensation takes place and separated carbon burning with insufficient air causes dense smoke. Small quantities of oil with excess air should be burned until the burner block becomes red hot to assist in the vaporization of the oil and to maintain ignition. A baffle in the form of a steel bar inserted from the outside and projecting in front of the burner will assist in lighting most oil burners, because it keeps the velocity of the atomized oil below that of ignition, and affords the mixture an opportunity to light before passing through the furnace chamber.

When lighting a furnace involving several burners, it is best to properly light one or two at a time, rather than to attempt to light all burners at once. The reason is that unburned combustion gases constitute an effective fire extinguisher and several improperly adjusted burners will interfere with the lighting of others.

A new furnace after construction should be slowly dried out with gradually increasing temperature to avoid spalling and cracking. This process should take two or three days, while the moisture in the brick and clay is slowly converted to steam and released without damage to the brick structure. In heating a large furnace to 2000°F., a good schedule of drying is as follows, although a considerable variation can be made: 10 hr. below 500°F.; 8 hr. below 1000°F.; 8 hr. below 1500°F.; and 8 hr. below 2000°F., giving a total time of 34 hr.

After the furnace has been heated to temperature and the doors closed, the total flue area should be partially closed until a pressure of about 0.01 in. water exists in all parts of the furnace. Temperature uniformity in the furnace may be regulated by closing the proper flues when regulating to the proper pressure. In general, the flues at hotter portions of the furnace should be closed to force more gas and heat toward flues left open in the colder portions of the furnace.

Liquefied Petroleum Gases

By George R. Benz*

Introduction—Liquefied petroleum gases for industrial use are available in two commercial grades, propane and butane. Commercial propane consists, essentially of propane and propylene, with very small amounts of ethane, butanes and butylenes. Commercial butane consists, essentially of butanes and butylenes, with small amounts of propane and propylenes. These fuels are manufactured at natural gasoline plants and refineries.

Properties of Liquefied Petroleum Gases—Liquefied petroleum gases and natural gas have similar combustion characteristics. Natural gas is composed principally of the paraffin hydrocarbons, methane and ethane. Liquefied petroleum gases are likewise composed principally of paraffin hydrocarbons. However, where obtained from refineries, olefin hydrocarbons are also present. Some of the most important and useful properties of commercial grades of propane and butane are shown in Table I. Table II shows comparative data for typical industrial gases and propane and butane.

Table I
Average Properties of Liquefied Petroleum Gas Products

	Commercial Propane	Commercial Butane	Pure Propane	Pure Normal Butane
Vapor Pressure psi.				
at 70°F.	122	31	108	17
at 90°F.	165	49	148	30
at 100°F.	190	59	172	38
at 105°F.	204	65	184	42
at 130°F.	282	97	257	67
Sp.gr. of Liquid (60°/60°F.)	0.511	0.582	0.509	0.584
Initial Boiling Point at 14.7 psi. Abs., °F.	-51	15	-44.1	30.9
Weight per gal. of Liquid at 60°F., lb.	4.26	4.84	4.239	4.864
Mean Coefficient of Thermal Expansion, Liquid:				
0-50°F.	0.00145	0.00104	0.00143	0.00096
50-100°F.	0.00184	0.00122	0.00180	0.00113
Dew Point at 14.7 psi. Abs., °F.	-45	24	-44.1	30.9
Specific Heat of Liquid, B.t.u./lb./°F. at 60°F.	0.587	0.549	0.596	0.556
Cu.ft. of gas at 60°F., 30"Hg per gal. of Liquid at 60°F.	36.18	31.46	35.81	30.81
Specific Volume of Gas, cu.ft./lb. at 60°F., 30"Hg.	8.50	6.50	8.451	6.333
Specific Heat of Gas, B.t.u./lb./°F. at 60°F. (Cp).	0.401	0.382	0.410	0.388
Sp.gr. of Gas (Air=1) at 60°F., 30"Hg.	1.53	2.01	1.546	2.053
Ignition Temperature in Air, °F.	920-1020	900-1000	920-1020	900-1000
Max. Flame Temperature in Air, °F.	3725	3725	3725	3735
Gas in Air for Max. Flame Temp., %	4.2-4.4	3.3-3.4	4.05-4.3	3.15-3.4
Max. Rate of Flame Propagation in 25 mm. Tube:				
Cm. per sec.	85.9	87.1	82.0	82.0
In. per sec.	33.8	34.3	32.0	32.0
Limits of Inflammability in Air, % Gas in Gas-Air Mixture:				
At Lower Limit, %	2.4	1.0	2.4	1.9
At max. Rate of Flame Propagation, %	4.7-4.9	3.7-3.9	4.6-4.8	3.6-3.8
At Upper Limit, %	9.6	8.6	9.5	8.5
Required for Complete Combustion:				
Cu.ft. O ₂ per cu.ft. Gas.	4.9	6.3	5.0	6.6
Cu.ft. Air per cu.ft. Gas.	23.4	30.0	23.9	31.1
Lb. O ₂ per lb. Gas.	3.59	3.54	3.631	3.581
Lb. Air per lb. Gas.	15.52	15.3	15.71	15.49
Products of Complete Combustion:				
Cu.ft. CO ₂ per cu.ft. Gas.	3.0	3.9	3.0	4.0
Cu.ft. H ₂ O per cu.ft. Gas.	3.8	4.6	4.0	5.0
Cu.ft. N ₂ per cu.ft. Gas.	18.5	23.7	18.9	24.6
Lb. CO ₂ per lb. Gas.	3.0	3.1	2.996	3.030
Lb. H ₂ O per lb. Gas.	1.5	1.5	1.635	1.551
Lb. N ₂ per lb. Gas.	11.9	11.8	12.08	11.91
Ultimate CO ₂ , % by Volume.	13.9	14.1	13.9	14.1
Latent Heat of Vaporization at Boiling Point:				
B.t.u. per lb.	184	167	183	165
B.t.u. per gal.	784	808	776	803
Total Heating Values (After Vaporization):				
B.t.u. per cu.ft.	2537	3261	2566.3	3368.7
B.t.u. per lb.	21570	21180	21688	21334
B.t.u. per gal.	91800	102600	91935	103769

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Storage and Vaporization—Propane and butane are shipped in special pressure type tank cars, tank trucks, and in small cylinders. Tank cars and tank trucks are unloaded, by pump or pressure differential, into the plant storage system. Plant storage tanks are constructed by fusion welding, in accordance with Section VIII, A.S.M.E. Unfired Pressure Vessel Code, and installed in accordance with rules and regulations of the National Board of Fire Underwriters, or other insurance or regulatory body having jurisdiction. Pressure type storage tanks are used, 80 lb. working pressure for butane, and 200 lb. working pressure for propane.

Propane and butane are piped about the plant as a gas, consequently require vaporization or gasification prior to distribution. This is accomplished by supplying the latent heat of vaporization and releasing the pressure. Vaporization is automatic, and in accordance with the plant fuel demand. In most propane installations, the gas is withdrawn from the vapor space above the liquid in the storage tank and passed into the plant piping, after passing through suitable regulators. When the fuel requirements are large, or when butane is used, a separate vaporizer is employed.

Table II
Composition and Combustion Characteristics of Various Fuel Gases

Constituents of Gases Shown, % by Volume.	Bituminous Producer Gas ¹	Oil Gas Protero 1920 ¹	Coke Oven Gas ¹	Natural Gas, Oil City, Pa. ¹	Carburized Blue Water Gas ¹	Blue Water Gas ¹	Industrial Propane ²	Industrial Butane ²
CO	27.0	6.8	6.3	...	33.4	42.8	...	...
CO ₂	4.5	1.0	1.8	...	3.9	3.0	...	...
H ₂	14.0	59.2	53.0	...	34.6	49.9	...	...
N ₂	50.9	2.7	3.4	1.10	7.9	3.3	...	...
O ₂	0.6	0.1	0.2	...	0.9	0.5	...	...
CH ₄	3.0	25.4	31.6	67.60	10.4	0.5	...	...
C ₂ H ₆ .....	...	...	...	31.30	...	...	2.0	...
C ₃ H ₈ .....	...	3.8	2.7	...	6.7	...	...	...
C ₄ H ₁₀ .....	...	...	...	...	...	...	19.0	...
C ₅ H ₁₂ .....	...	...	...	...	...	...	76.0	5.0
C ₆ H ₁₄ .....	...	1.0	1.0	...	2.2	...	...	...
C ₇ H ₁₆ .....	...	...	...	...	...	...	1.5	49.6
C ₈ H ₁₈ .....	...	...	...	...	...	...	...	28.4
C ₁₀ H ₂₂ .....	...	...	...	...	...	...	1.50	18.5
C ₁₂ H ₂₆ .....	...	...	...	...	...	...	...	0.5
Sp.Gr. (Air-1)	0.66	0.35	0.42	0.71	0.65	0.53	1.53	2.01
B.t.u. per Cu.Ft.	150	575	588	1232	536	308	2737	3261
Gross Products of Combustion Per Cu. Ft. of Gas.								
CO ₂	0.35	0.47	0.51	1.30	0.74	0.46	3.0	3.9
H ₂ O	0.19	1.21	1.25	2.29	0.75	0.51	3.8	4.6
N ₂	1.49	3.91	4.13	0.26	3.54	1.82	18.5	23.7
Total (dry) ..	1.84	4.38	4.64	10.56	4.28	2.28	21.5	27.6
Ultimate CO ₂ %	19.0	10.7	11.0	12.3	17.2	22.3	13.9	14.1
Gross B.t.u. per Cu.Ft. of Mixture	67.0	97.2	95.0	97.1	99.9	94.5	104.0	105.2
Flame Temperature Corrected for Dissociation, °F.	3160	3725	3660	3620	3815	3800	3600	3615
Vol. Required in Cu.Ft.								
O ₂	0.259	1.026	1.085	2.446	0.918	0.473	4.9	6.3
N ₂	0.981	2.884	4.105	9.254	3.45	1.787	18.5	23.7
Air	1.24	4.91	5.19	11.70	4.37	2.26	23.4	30.0

¹A.G.A. Handbook "Combustion."

²Phillips Petroleum Co.

Undiluted propane gas is piped about the plant at either low or high pressure, the exact pressure being determined by the type of burner equipment.

Undiluted butane gas may be piped about the plant at low pressure, provided the temperature does not fall below the dew, or condensation point. If high pressure

gas is required, butane must be diluted or partially mixed with air prior to distribution. Dilution with air lowers the dew point.

Combustion Equipment—Table II shows that the rate of flame propagation (speed of combustion) of propane and butane is low, but comparable to that of natural gas. This "slow burning" characteristic permits a lower air-gas mixture velocity through burner ports or nozzles without back firing, as well as allowing the operation of certain types of burner equipment with a lower manifold pressure, with corresponding greater range of "turn up" and "turn down".

The comparative efficiency of various gaseous fuels is in direct relation to the available heat of the gas, all factors of furnace construction and operation being equal. The available heat of a fuel is the difference between the gross B.t.u. value and the amount of heat contained in the products of combustion at the temperature under consideration. The available heat of both propane and butane is high, and is at 2000°F. approximately 50% of the gross B.t.u. value. Propane and butane contain no noncombustible constituents such as nitrogen, carbon dioxide, or water vapor.

Tables I and II show important combustion data for propane and butane, the most important to the engineer being the products of combustion, ultimate CO₂, air required for combustion, rate of flame propagation, flame temperature and average composition. Propane and butane are generally used through the various types of air-gas combustion equipment and burners.

Fuel Oil

By J. E. Hamilton,* R. T. Goodwin† and R. C. Brierly†

Fuel oil, as the term is broadly used, covers a wide range of products ranging from those similar to kerosene down to fairly heavy residua.

Grades of Fuel Oils—Standardization has led to a generally accepted division of fuel oil into five classes based on several physical properties. The Commercial Standard, (CS12-38), gives the property limits of the various grades as shown in Table I.

The first three grades in Table I are the domestic heating oils. In general, Grades 1-3 are distillates and Grades 5 and 6 are residual products or blends of residua and distillate from the crude oil refining process.

Industrial fuel oil, unless purchased under a service contract containing definite performance provisions, may meet all the specification tests, but may differ from previous deliveries. The product being manufactured may be contaminated, furnace refractories may fail much more rapidly than before, smoke problems may be increased, or fouling may develop in some part of the oil handling systems. Any of these things, and others, may happen due to changes in the oil which are not apparent in the tests which have been developed.

Properties of Fuel Oils—The characteristics of fuel oil which are of interest are:

Physical characteristics:

1. Viscosity
2. Gravity
3. Flash point
4. Fire point
5. Physical impurities
 - (a) Water
 - (b) Grit and fibrous materials
 - (c) Solid bodies
6. Pour point

Chemical characteristics:

1. Composition
2. Heat value
3. Uniformity
4. Stability
5. Acidity
6. Impurities, such as sulphur

Viscosity—Viscosity is that property of fuel oil which determines its resistance to flow. It is measured by an instrument, the viscosimeter, which in all its different types comprises a means for determining the time in which a measured quantity of oil at a standard temperature goes through a tube of standard dimensions. The instrument commonly used in the United States is the Saybolt of which there are three instruments of different flow tube dimensions. The Saybolt Universal viscosimeter is usable for most lubricating oils and for fuel oils in the upper range of the domestic heating types. In practice, the Saybolt Universal viscosimeter is used up to flow period of between 500-1000 sec., at which point the Furol viscosimeter is applicable. Since viscosity varies with temperature, the principal requirement of any viscosity test is maintenance of the oil under test at specified temperature. Most tests are made at the following standardized temperatures: Saybolt Universal, 32°F. and 100°F.; and Furol, 77°F. and 122°F.

The principal direct effects of viscosity on utilization are in handling the fuel oil and in atomizing at the burners. Viscosity alone being considered, the only upper limit for practical utilization is the ability of the equipment to raise the temperature of the oil to a point where it will flow and atomize. Any lower viscosity limit is acceptable except that better construction of joints and seams is needed to prevent leakage with the extremely fluid types.

The upper limit must be determined by the location and facilities of the plant. In general, it can be stated that Grade 5 fuel oil is satisfactory for use in almost any system where the temperature between the tanks and the preheaters can be maintained above 32°F. and in the preheaters can be raised to at least 125°F. Grade 6 fuel oil can be used in any system where the temperature before the preheater can be maintained above 100°F. and after the preheater can be delivered to the burner at a temperature of 240°F. For fuel oil of viscosity above the upper limit of Grade 6 the system should be so designed that the temperature before the preheater can be maintained sufficiently high to prevent the viscosity exceeding

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The statements, opinions and conclusions here published are those of the authors and in no way express the official opinion of the Navy Department.

Table I
Commercial Standard Specifications*
 (CS12-38)

Detailed Requirements for Fuel Oils
 Adopted May, 1938

Grade ^b	Flash Point, °F.	Min. Max.	Pour Point, °F.	Max.	Water and Sedi- ment, %.	Carbon Residue, %.	Ash, %.	Distillation Temperatures, °F.				Viscosity Seconds—	
								10% Point Max.	90% Point Max.	End Point Max.	Min.	Saybolt Universal at 100°F. Max.	Saybolt Furol at 122°F. Max.
No. 1 Fuel Oil—A distillate oil for use in burners requiring a volatile fuel.	100		165	15 ^c	Trace	0.05 ^d on 10% residue		410		560 ^e			
No. 2 Fuel Oil—A distillate oil for use in burners requiring a moderately volatile fuel	110		190	15 ^c	0.05	0.25 ^f on 10% residue		440	600				
No. 3 Fuel Oil—A distillate oil for use in burners requiring a low viscosity fuel.	110		230	20 ^c	0.10	0.15 straight		675	600 ^g		55		
No. 5 Fuel Oil—An oil for use in burners requiring a medium viscosity fuel	130				1.00		0.10				60	40	
No. 6 Fuel Oil—An oil for use in burners equipped with pre-heaters requiring a high viscosity fuel	150				2.00 ^h							300	45

^aRecognizing the necessity for low sulphur fuel oils used in connection with heat treatment, nonferrous metal, glass and ceramic furnaces and other special uses, a sulphur requirement may be specified as follows: Grade No. 1 and 2, 0.05% max., Grade No. 3, 0.75% max., Grade No. 5 and 6 no limits. Other sulphur limits may be specified only by mutual agreement between the buyer and seller.

^bIt is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

^cLower or higher pour points may be specified whenever required by conditions of storage or use. However, these specifications shall not require a pour point lower than 0°F. under any conditions.

^dFor use in other than sleeve type blue flame burners, carbon residue on 10% residue may be increased to a max. of 0.12%. This limit may be specified by mutual agreement between the buyer and seller.

^eThe maximum end point may be increased to 590°F. when used in burners other than sleeve type blue flame burners.

^fTo meet certain burner requirements the carbon residue limit may be reduced to 0.15% on 10% residue.

^gThe minimum distillation temperature of 600°F. for 90% may be waived if A.P.T. gravity is 26 or lower.

^hWater by distillation, plus sediment by extraction. Sum, max. 2.0%. The maximum sediment by extraction shall not exceed 0.50%. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

500 Saybolt-Furol-Seconds and after the preheater to permit reducing the viscosity to at least 200 Saybolt-Universal-Seconds.

Gravity—Gravity of fuel oil is measured by an arbitrary scale which is related to the specific gravity. In the United States the scale used is that known as A.P.I. (American Petroleum Institute) which is based on specific gravity using the moduli:

$$\text{For oils lighter than water, A.P.I.} = \frac{141.5}{\text{sp.gr.}} = 131.5$$

$$\text{For oils heavier than water, A.P.I.} = 145 - \frac{145}{\text{sp.gr.}}$$

Gravity is measured by hydrometers graduated to the A.P.I. scale. Since the hydrometer reading is dependent upon displacement of oil whose gravity is being measured, the weight of the oil displaced will vary with the coefficient of expansion of the oil. Gravity is ordinarily measured at whatever temperature the oil may happen to be, coincidentally measuring that temperature, and then correcting the gravity to a standard temperature of 60°F. by the use of tables published by the United States Bureau of Standards.

At present fuel oils of the industrial grades are obtainable at gravities ranging from 3 or 4 A.P.I. (1.021 sp.gr.) to 25 or 30 A.P.I. (0.876 sp.gr.). The heavier the oil the greater its B.t.u. content, per unit volume; hence, since oil is commonly sold on a volumetric basis, it is highly advantageous to obtain oil of the lowest gravity (highest sp.gr.) if it has other acceptable characteristics.

Flash Point—Flash point is the temperature at which the oil first emits sufficient gas to cause a momentary, nonsustained flame when subjected to standard flame. Standardized instruments for measuring flash point are either the closed cup type or the open cup type. In general the open cup readings are about 20-30° higher than the closed cup which is the instrument usually used for specification tests. The temperature of the oil to be tested is raised in the instrument until the first nonsustained flame appears when a lighted taper having a flame of standard size is applied near the surface. Flash points may vary from slightly above atmospheric temperatures to well above 200°F. For kerosene and domestic heating oils many states have laws limiting flash points to not less than some figure which possibly averages around 100°F. Fire due to low flash point must be initiated by a flame. For fuel oils above the domestic range normal limits have always been either 150 or 175°F. as a minimum. It is considered that a minimum limit of 150°F. is entirely satisfactory.

Fire Point—Fire point is measured by increasing the temperature above the flash point until a sustained flame of at least 30 sec. duration is initially produced. Fire point has never been specified for fuel oil. Its only possible connection with utilization is in its relationship to the ease of starting a fuel oil fire. Practical methods of starting fire are such that any fuel oil can be ignited and once ignition has taken place it will continue. There is no benefit to be derived from further consideration of fire point.

Water as an Impurity—Water can enter fuel oil either through condensation or contamination. This can occur either before or after the oil is delivered to the storage system. It was previously accepted as satisfactory to test water by gravitational separation. Acceleration of operation was obtained by use of a centrifuge with a standard radius, speed of rotation, and sample test tube. This method was undoubtedly satisfactory for fuel oils of the straight run types where the water was interspersed through the body of the oil as free water and where the oil has a sp.gr. of less than 0.95. For close determination the method is wholly unsuitable for many cracked oils or for a majority of oils whose gravities are close to or less than that of water. For any oil a true determination of water content can be obtained by a distillation test.

It is possible for water to be present in very minute globules up to as much as 5% if highly emulsified. It is very improbable that a purchaser need protect himself against any limits beyond about 5%. Up to this amount water might be present without being readily discernible.

Water reduces the fuel value of the oil, not only by the lesser volume of actual oil but also by the furnace loss in vaporizing the water. It is customary in specifications not to exceed 1% of water at the contract price and not to exceed 2% with a price adjustment for the water in excess of 1%.

Grit and Fibrous Materials as Impurities—It is possible for fuel oil to pick up gritty and fibrous materials during the refining process. All such foreign material can be removed by straining. There are no standard methods of test for determining the presence of these materials, but their possibility should be obviated by installing at some point in the system an adequate strainer to remove all sizeable foreign bodies.

Solid Bodies as Impurities—Solid bodies in the fuel oil may be of a mineral nature which became entrained in the same manner as grit, or they may be particles of carbon formed in the oil during the refining process. Protection against non-combustible impurities may be obtained by a crucible burning test where combustion is carried to completion and the increase in weight of the crucible after burning represents the weight of the noncombustibles in the sample. The test is difficult to control.

Pour Point—Pour point is the lowest temperature at which oil will flow or pour. It is a function of temperature. Pour point is measured by reducing the temperature of a small quantity of the oil in a test tube until it will no longer flow. Pour points run from well below zero to in the order of 80°F., or higher, pour point of straight run residual oil will run considerably higher than those which are residual of cracking processes.

In practice large bodies of oil do not congeal at as high a temperature as will a small sample of the oil in a test tube. There is practically no need for specifying any pour point limitation where the oil in storage will not be subjected to temperature below freezing. Where storage tanks of fuel oil are exposed to atmospheric temperatures in the winter, it would be advisable to have a maximum pour point limit about 10% higher than the expected minimum temperature of the oil.

Chemical Composition—The two principal constituents of fuel oils are hydrogen from 8-20% by weight and carbon from 80-92% by weight on a water-free basis. Other elements, which are impurities in the pure hydrocarbons, may be present. Sulphur which may be in amounts from a trace to nearly 5% is the most common impurity. Other possible constituents, rarely present in amounts over 0.5%, are the halogens, metals, and salts.

It is possible that some additional impurities may enter the fuel oil as a contaminating residue from the refining process. Some refineries use ammonia, lime, sulphuric acid and probably other reagents in different phases of treatment which may be added to the residual fuel oil.

Since the thermal value of hydrogen oxidation is greater than that of carbon, the more valuable fuel per lb. is that with the higher percentage of hydrogen. However, since United States practice has been standardized on volumetric units for sale of fuel oil, the advantage is reversed as has been mentioned above because the high-hydrogen oils are lighter. For practical purposes, the carbon-hydrogen ratio is sufficiently well established by the sp.gr. measurement (which increases with the percentage of carbon) that hydrogen content may be neglected.

When heating steel in an open chamber, it should be remembered that hydrogen burns to H₂O and gives a harsh cutting flame.

Heat Value—Heat value is a measure of the amount of energy which is obtainable from the oil when burned. There have been a number of empirical formulae developed for determining the calorific value by using other measurable characteristics. Inchley's formula based on the ultimate analysis is:

$$\text{B.t.u. per lb.} = 13,500 \text{ C plus } 60,890 \text{ H.}$$

The Naval Boiler Laboratory formula is:

$$\text{B.t.u. per lb.} = 17,751 \text{ plus } 53.4 \times \text{the A.P.I. gravity at } 60^\circ\text{F.}$$

Either of the above formulae will give results close enough for practical purposes. The more accurate method is by measurement in a bomb calorimeter.

Uniformity—Fuel oil which is a residual product from the same process will be practically homogeneous throughout except for the slight deposition of sludge settling in storage. The sludge may be greater with some cracked residues than with normal straight run residue. It should offer no difficulties in service if the suction line on the storage tank is so arranged that the suction is above the sludge line.

It is possible to blend a viscous residue with a low viscosity distillate and obtain a very unsatisfactory product although theoretically, they should be exactly correct as to viscosity. The reason appears to be that there is such a thing as incompatibility between some residues and some distillates. Except in cases of incompatibility,

any blend properly made will remain uniform indefinitely, that is, there is no tendency for the two constituents to separate once they have been well blended.

Stability—This term as here used applies to the freedom from chemical change of the fuel oil due to conditions of pressure, temperature, or age, either in storage or in the system until burned. For a straight run product there is little probability that any chemical change will occur in practice. Maximum temperatures attained prior to ignition are several hundred degrees below cracking temperature. In storage at moderate temperatures it would take an extremely long time to cause any of the chemical changes which are accelerated by heat. However, for cracked fuel oils it has been found that, even though the oil has been subjected to cracking temperatures, it is not necessarily stable at temperatures encountered in the fuel oil system. It is not definitely known whether this change is a chemical or a physical change.

Acidity—The normal opacity of fuel oil makes the litmus or other color reaction change inapplicable. It is possible by setting up a suitable arrangement to run distilled water through the oil (known as washing) and then test the recovered water for acidity. This test should reveal any extreme acid condition.

Sulphur as an Impurity—Sulphur in a fuel oil is probably rarely present in the free state. It is normally present in the form of hydrogen sulphide or other sulphur derivatives. Any fuel oil whose content of hydrogen sulphide is apparent from the odor on delivery should be rejected.

Sulphur present in any form will, after combustion, be present as sulphur dioxide. Sulphur dioxide in the gases of combustion will cause no difficulty until it is cooled below the boiling point of water. If the gases of combustion are released to the atmosphere at temperatures well above 212°F. so that they disperse before condensation, no destructive concentration of sulphurous or sulphuric acid can be encountered. The greatest difficulty is due to pockets in the combustion or flue spaces where gases of combustion may collect and condense. Since such spaces will also collect soot, the sulphur dioxide dissolved by the condensate will form sulphurous or sulphuric acid which will be absorbed by the soot and is highly corrosive to contiguous metal. Proper design or frequent thorough cleaning will minimize this difficulty.

If the equipment for heat treating of metals is so designed that the gases of combustion themselves impinge directly upon the metal being treated it is possible that sulphur contamination will occur. Also, it is detrimental to a number of alloys, especially heat and corrosion resisting alloys of the high nickel-chromium type and to Chromel-Alumel thermocouples. Sulphur may be present in fuel oil in quantities as high as 5%, but such a percentage is rare. As fuel, this reduces the heat value slightly. Where the heating equipment requires direct contact between the gases of combustion of the fuel oil and the product, it is recommended that a sulphur limit of 0.5% be specified.

Equipment—Where the location of a plant is favorable to the use of fuel oil, the equipment should be made, or modified, to fit all probable kinds of fuel oil. This should certainly be done in installing new equipment. In most cases old equipment can be modified to permit utilization of any possible fuel oil without serious difficulties.

Fuel Storage System—If local regulations will permit, the fuel storage system should be located at a reasonably high elevation above the furnaces. The total tankage should be divided into four tanks or four subbatteries of tanks so that one can at all times be in use, one standby for use, one empty, cleaned and awaiting delivery, and one being cleaned. It is advisable to receive fuel oil only into clean tanks and not to mix it with any oil remaining from previous deliveries.

All fuel oil tanks should be equipped with steam heating coils of sufficient outside surface to maintain the oil in the tank at a temperature of at least 80°F., using saturated steam at whatever pressure may be available. For plants located where extreme winter weather conditions may be encountered, a saving in fuel will probably compensate for insulation on the tanks.

Each tank should have a pipe connection at the lowest point in the tank for use in cleaning or draining water and sediment.

Fuel Supply System—Connections to the tanks should be so made that suction in the tank will be above the sludge line. All connections should be so manifolded that any tank can be separately connected. In calculating the pipe size, allow a considerable margin to reduce flow restrictions. In calculating flow losses, each fitting and 90° bend may be equivalent to from 50-100 feet of piping. Properly

designed fittings, welded into the pipe, will reduce these figures considerably. A double basket or similar strainer should be installed on the discharge side of the pump. However, strainers are also installed on the intake side of the pump.

Pumps of the screw type are successfully used even in cases where there is not a positive pressure on the supply side. A priming pump is used in these cases. Motor driven geared pumps are commonly used. These are of the positive displacement type and the excess oil is returned to the tank through a relief valve set at the desired operating pressure. Any pump, if properly designed, will handle fuel oil if its viscosity (either before or after heating) is not greater than 700 Saybolt-Furol-Seconds.

In the event of fire or fuel oil system breakage, the supply line entering each building should be provided with a quick closing valve operable from either inside or outside the building.

Burning Equipment—The fire installation consists of the service pump, fuel oil preheaters, air registers, atomizers (commonly called burners), and fans or other draft forcing apparatus.

Fuel oil atomizers are of four general types: Mechanical pressure, mechanical centrifugal, air, and steam. The amount of work performed by an atomizer is definite and can be calculated in ft.-lb.

Mechanical pressure atomizers require high pressure piping systems and preheaters. Preheaters are usually operated on exhaust steam. They reduce the viscosity of the fuel oil to a point where droplets of fuel oil can be forced by pressure through the passages of the sprayer plate or tip and plug which forms the working portion of the device. The small passages in the sprayer plate or tip and plug are more apt to be clogged by sediment than the relatively larger ones of other type atomizers.

Centrifugal atomizers form mist-like fogs of fuel oil by means of a cup rotating at high speed together with a blast of air passing around its periphery. Moving parts tend to increase upkeep, and they occupy considerable space on the furnace, principally because air intermixing registers are required.

Steam and air atomizers are similar in construction. In both cases, the oil drooling at low pressure from an orifice is caught by a blast of air and steam and shattered into the form of finely divided particles, principally by impact. All air and steam atomizers may be subdivided into two principal types: The outside mixing and the inside mixing. Oil, in the former case, is reduced to fine particles outside the metal portions of the atomizer itself, and in the latter case, air or steam surrounds and entrains the oil particles, carrying them through an orifice which may be designed in such a manner that practically any shape of flame can be obtained. Thus, the use of a circular orifice will provide a conical flame; a horizontal slot, a "fish tail" flame.

The best type of atomizer to be used depends upon conditions existent in the plant.

Air Mixing—It is necessary that the atomized oil be thoroughly mixed with air in sufficient quantities for complete combustion. The oil and air mixture must be intimate; this is a function of the air register operating in conjunction with the atomizer. The air may be drawn into the furnace through the register or apertures either by the natural or forced draft.

On heat treating and drop forging furnaces and furnaces of this type, the air for combustion is usually supplied through the burner without the use of air registers.

The design of the combustion space should provide a "target" wall or baffle for the flame to play on so that it will not impinge directly on the metal being heated or the brickwork. The furnace dimensions should be sufficient to allow full combustion of the oil in the furnace. With cracked fuel oils these dimensions must be greater than for straight run oil. For additional information on industrial heating furnaces and types of burners see page 262.

Properties of Refractories

The properties of commercial refractory materials may differ because of impurities, location of the source of raw materials, bonding materials, and manufacturing processes. As the readers' interest may be with both the commercial and pure refractories, Tables I, II, and III give the chemical and physical properties of the commercial, and Table IV of the pure refractories.

Table I
Chemical Properties of Commercial Refractories

By F. H. Norton*

Material	Theoretical Composition	Reaction with Basic fluxes ¹	Reaction with Acid fluxes ¹	Resistance to Oxidation	Resistance to Reduction
Alumina (fused)	Al ₂ O ₃	Fairly rapid with fluid slags. Slow in cement kilns	Fairly slow	Good	Not affected
Carbon	C	Slow	Slow	Low above red heat	Not affected
Chromite	FeO.Cr ₂ O ₃	Slow	Slow	Low above red heat	Reduced to ferrochromium at high temp.
Fireclay	2SiO ₂ .Al ₂ O ₃	Rapid	Slow except at high temp.	Good	Not affected
Forsterite	2MgO.SiO ₂	Fairly slow	Fairly slow	Good	Not affected
Graphite	C	Slow	Slow	Good	Not affected
High alumina (diaspore)	Al ₂ O ₃ .H ₂ O	Fairly rapid with fluid slags. Slow in cement kilns	Slow at low and medium temp. Rapid except at low temp.	Good	Same as alumina
Magnesite	MgO	Slow	Rapid except at low temp.	Good	Reduced to Mg at high temp.
Mullite	2SiO ₂ .3Al ₂ O ₃	Rapid	Fairly slow	Good	Not affected
Porcelain (refractory)	2SiO ₂ .3Al ₂ O ₃	Rapid	Fairly slow	Good	Not affected
Silica (fused)	SiO ₂	Rapid	Slow	Good	Not affected except at high temp.
Silica (ganister)	SiO ₂	Rapid	Slow	Good	Same as fused silica
Silicon carbide	SiC	Fairly rapid	Slow	Fair above red heat	Not affected
Spinel	MgO.Al ₂ O ₃	Slow	Fairly rapid	Good	Not affected
Zircon (electrically fused)	ZrO ₂ .SiO ₂	Fairly rapid	Slow	Good	Not affected except at high temp.
Zirconia (electrically fused)	ZrO ₂	Fairly slow	Slow	Good	Forms carbides at high temp.

*Prof., Mass. Institute of Technology, Cambridge, Mass.

The slag resistance of a refractory is influenced by its physical as well as its chemical properties. Therefore, a dense nonporous structure without flaws is desirable.

Table II
Physical Properties of Commercial Refractories
By F. H. Norton*

Material	Fusion point, °F. ¹	Temp. °F. for 10% deforma- tion under 25 psi.	Mean coef. linear expansion between room temp. and shrink temp. X 10 ⁻⁵ /°F.	True sp.gr.	Wt. of a Std. 9-in. brick	Spalling resistance	Hardness	Specific heat 0-1200°F.
Alumina (fused)	3725	3100-3200	0.43	4.0	8.5	Fair	9	0.23
Carbon	Very high	.....	0.30	1.7-2.0	.....	Excellent	.....	0.30
Chromite	3450-3950	2550-2900	0.56	4.3-4.5	11	Poor	5.5	0.22
Fireclay	2730-3150	2550-2850	0.25-0.30	2.6-2.75	7.5-8.5	Good	2.5	0.23
Forsterite	3430	.....	.....	3.2-3.3	9.0	Fair	6-7	0.25
Graphite	Very high	.....	0.43	2.1-2.3	.....	Excellent	1-2	0.30
High alumina (diaspore)	3100-3350	2820	0.28	3.0-3.5	8.0	Good	6.5-7	0.23
Magnetite	3990-5070	2550 (sheared)	0.56-0.83	3.4-3.6	10.0	Poor	5-5.5	0.27
Mullite	3270	3150	0.30	3.0	8.5	Good	6-6.5	0.18
Porcelain (refractory)	2900-3250	.....	0.30	2.7-3.0	.....	Good	6-6.5	0.18
Silica (fused)	Devitrifies at 2000	.....	0.03	2.2	.....	Excellent	.7	0.23
Silica (ganister)	3100-3180	3000	5.60-0.46	2.3-2.5	6.0	Good at high temp. only	7	0.23
Silicon carbide	(decomposes)	3180	0.24	3.1-3.3	9	Excellent	9.5	0.20
Spinel	3450-3800	2700-2900	0.42	3.5	10	Poor	7.5-8	0.25
Zircon (electrically fused)	4000-4600	.....	0.22	4.7	12.5	Excellent	7.5	.....
Zirconia (electrically fused)	4500-4800	.....	0.30-0.80	5.7	15	Fair	6.5-7.5	0.20

*Prof., Mass. Institute of Technology, Cambridge, Mass.

¹The fusion point of refractories is sometimes given in terms of cone numbers (P.C.E.) but as this is adding another temperature scale to evaluate this property, the Fahrenheit scale is recommended in engineering work.

Table III
Thermal and Electrical Conductivity of Commercial Refractories
By F. H. Norton*

Material	True thermal conductivity, ¹ B.t.u./sq. ft./in./° F./hr.					Electrical resistivity, ¹ ohms/cm. cube				
	200	400	800	1200	1600	2000	2400° F.	1300° F.	2200° F.	2700° F.
Alumina (fused).....	19	20	22	24	27	30	32	.....	.....	.....
Carbon.....	25	.....	.....	.....	.....	.....	.....	.....	.....	.....
Chromite.....	5	6	7	8	10	11	12	.....	.....	.....
Fireclay.....	5	6	7	8	10	11	12	30,000	1,000	600
Forsterite.....	.....	6	7	8	10	11	12	.....	.....	.....
Graphite.....	.....	60	.....	.....	.....	.....	.....	.....	.....	.....
High alumina (diaspore).....	5	6	7	8	10	11	12	35,000	900	.....
Magnesite.....	45	40	35	31	27	25	24	.....	100,000	2,000
Mullite.....	.....	8	9	10	12	13	14	.....	50,000	3,000
Porcelain (refractory).....	.....	14	15	17	18	19	20	{ 80,000 500,000	.....	.....
Silica (fused).....	14	.....	.....	.....	.....	.....	.....	10,000,000	500,000	.....
Silica (ganister).....	6	7	8	9	11	12	13	80,000	16,000	5,000
Silicon carbide (recrystallized).....	.....	170	140	120	100	90	80	.....	2.5	1.6
Spinel.....	.....	10	11	12	13	14	15	.....	.....	.....
Zircon.....	.....	.....	.....	11 to 14	.....	.....	.....	140,000	.....	.....
Zirconia.....	.....	8	9	10	12	13	14	.....	2,000	400
Kaolin refractory insulator.....	1.2	1.3	1.6	2.0	2.6	3.1	3.2	.....	.....	.....
Block insulator.....	0.6	0.7	0.8	.....	.....	.....	.....	.....	.....	.....

* Prof., Mass. Institute of Technology, Cambridge, Mass.

¹The figures on electrical resistivity are approximate because slight amounts of impurities greatly influence them. The thermal conductivity values are not exact as there are considerable variations in the published results.

Table IV
Properties of Pure Refractory Materials¹
By S. M. Phelps†

Material ²	Composition of the pure material Formula	Constituents, %	Melting point	True sp.gr.	Mohr's hardness	Mean sp. heat 20-1000°C. 68-1832°F.	Mean reversible thermal expansion 20-1000°C. X 10 ⁶ /°C.
Andalusite	Al ₂ O ₃ .SiO ₂	Alumina 62.85 Silica 37.15	1810°C. 3290°F.	3.20	7.5	0-100°C. 0.168	6.2*
Chromite	FeO.Cr ₂ O ₃ ³	Chromic oxide..... 68 Ferrous oxide..... 32	2180°C. 3956°F.	4.5	5.5	0.22*	8.0*
Corundum	Al ₂ O ₃	Alumina 100	2050°C. 3722°F.	Alpha 4.0	9	0.304*	8.5
Cyanite (Kyanite)	Al ₂ O ₃ .SiO ₂	Alumina 62.85 Silica 37.15	1810°C. 3290°F.	3.6±	4-7		4.9**
Diaporite ⁴ (Diaspore)	Al ₂ O ₃ .H ₂ O	Alumina 85.1 Water 14.9	2050°C. 3722°F.	3.4-3.5	6.5-7	.	6.5*
Dolomite	CaCO ₃ .MgCO ₃	Lime 30.4 Magnesia 21.9 Carbon dioxide..... 47.7	Dissociates at high temperatures	2.81-2.95	3.5-4	20-98°C. 0.222	14.0
Dumortierite	8Al ₂ O ₃ .6SiO ₂ .B ₂ O ₃ .H ₂ O	Silica 64.6 Alumina 28.5 Boron oxide..... 5.5 Water 1.4	1810°C. 3290°F.	3.30	7		5.2*
Forsterite	2MgO.SiO ₂	Magnesia 57.3 Silica 42.7	1910°C. 3470°F.	3.22	6-7	20-100°C 0.22	10.5*
Graphite	C	Carbon 100	Above 3000°C. Above 5432°F.	2.25	1-2	0.29	2.2
Magnesia spinel	MgO.Al ₂ O ₃	Magnesium oxide... 28.2 Alumina 71.8	2135°C. 3875°F.	3.6	8	0.257	8.5
Mullite	3Al ₂ O ₃ .2SiO ₂	Alumina 71.8 Silica 28.2	1810°C. 3290°F.	3.03		20-800°C. 0.175	5.3 ⁷
Periclase ⁴ (Magnesia)	MgO	Magnesium oxide... 100	2800°C. 5072°F.	3.64-3.67	5.5-6	0.285	13.5*
Quartz ⁵ (Quartzite)	SiO ₂	Silica 100	1400°C. ¹⁰ 2552°F.	2.653	7	0.263*	20-300°C. 32.6 ¹¹ 300-1135°C. 4.6
Silicon carbide	SiC	Silicon 70 Carbon 30	Dissociates ¹² 2250°C. 4082°F.	3.17-3.21	9-10	0.19 ¹³	5.2 ¹⁴
Sillimanite	Al ₂ O ₃ .SiO ₂	Alumina 62.85 Silica 37.15	1810°C. 3290°F.	3.24	6.5-7.5	0.175	...
Zircon (Zirconium silicate)	ZrO ₂ .SiO ₂	Zirconium oxide... 67.1 Silica 32.9	2550°C. 4622°F.	4.7	7.5	21-51°C. 0.132	4.5
Zirconia (Zirconium oxide)	ZrO ₂	Zirconium 73.9 Oxygen 26.1	2700°C. 4892°F.	5.5-6.0	6.5	0.16	6.6 ¹⁵

For footnotes, see next page.

- †Refractories Fellowship, Mellon Institute of Industrial Research, Pittsburgh.
- ‡Because of the variation in the properties of different types of fireclays, they were not included in this table.
- §The results marked with asterisk (*) were obtained from commercial products.
- *General chemical formula for chromite is $RO \cdot R_2O_3$. The RO oxide is usually FeO and may be replaced in part by MgO, while the R_2O_3 is mostly Cr_2O_3 , but may be replaced in part by Al_2O_3 and Fe_2O_3 .
- †Indian.
- *Commercial diasporite is composed of diasporite grains bonded with clay.
- ‡Probably close to 0.26.
- †Synthetic, pure.
- *Magnesite is amorphous or crystalline like periclase, depending upon the heat treatment it has received.
- *Ganister is the commercial form for use in refractories, about 98% silica.
- †Cristobalite is the stable form of silica above 1470°C . and has the melting point of 1713°C . (3115°F .).
- †Silica brick.
- †Oxidation may begin at 900°C . (1652°F .).
- †Varies greatly with temperature.
- †Recrystallized.
- †Pure material sintered.

Pyrometry*

Pyrometry deals with the measurement of all temperatures above about 950°F. The principal methods of pyrometry are the thermoelectric, the optical, and the radiation methods. The thermoelectric and the total-radiation methods can easily be extended to temperatures below 950°F.

Thermoelectric Pyrometry—Thermoelectric pyrometers may be satisfactorily used for measuring temperatures up to about 3000°F.

Principle of the Thermoelectric Pyrometer—In 1821 Seebeck discovered that if two dissimilar wires are joined together at both ends and one junction is heated, an electromotive force (emf.) or voltage is generated in the circuit. This phenomenon is called the thermoelectric effect. The discovery led to the development of the thermoelectric pyrometer, a simple form of which is illustrated by Fig. 1. It consists of a millivoltmeter connected to two wires of different metals, the other ends of which are joined together and placed in a furnace. The two wires of different metals joined together at one end constitute the *thermocouple*, one wire being the positive element and the other the negative element. The millivoltmeter is an instrument to measure the emf. or voltage generated.

Some thermocouples consist of two elements in the form of wires while others consist of a wire element within a tubular element.

In the thermoelectric circuit shown in Fig. 1 there are three junctions as follows: The junction of the two wires inside the furnace, often called the "hot junction," now generally referred to as the "measuring junction"; and the two junctions between the elements of the thermocouple and the copper wires connecting them to the millivoltmeter, A and A_1 . Although there are two such junctions in the arrangement shown in Fig. 1, the pair is commonly treated as a unit and often called the "cold junction," now more generally referred to as the "reference junction." Since we are concerned altogether with high temperatures, we shall adhere to the terms, "hot" and "cold," as they can lead to no misunderstanding.

At each of these junctions an emf. is generated which varies with the temperature of the junction, and the algebraic sum of these three emf.'s is the emf. measured by the millivoltmeter. If the temperature of the cold junction pair is maintained constant, then the resultant emf. as measured by the millivoltmeter varies only with the temperature of the hot junction.

Thermocouple Materials—The number of metals and alloys suitable for commercial use in thermocouples is rather limited for they must be resistant to oxidation, recrystallization, melting, and contamination at high temperatures; they must develop an emf. high enough to be measured without the use of delicate apparatus; and finally, they must be reproducible and readily obtainable in uniform quality.

The different combinations of materials in common commercial use for thermocouples are: Platinum vs. the alloy 87% platinum plus 13% rhodium; platinum vs. the alloy 90% platinum plus 10% rhodium; "Chromel" vs. "Alumel"; iron vs. "constantan"; and copper vs. "constantan." The last three pairs are commonly referred to as "base metal couples."

The useful life of a thermocouple depends not only on the maximum temperature to which it will be subjected, but also on the atmospheric conditions to which it will be exposed.

Platinum vs. platinum-rhodium thermocouples may be used up to a temperature of 3000°F., but they are easily contaminated and must be suitably protected at all times. Continuous subjection to temperatures above 2800°F. is not recommended.

There is no completely satisfactory material for long service in reducing gases. Stainless steel (iron-chromium-nickel alloy) is being used to a limited extent paired with Chromel, but the couple has not been standardized by the instrument companies.

The Chromel-Alumel thermocouple will generally be more satisfactory than the iron-constantan in oxidizing atmospheres at 1200-2200°F. Chromel-Alumel may be

*The article on thermoelectric pyrometers was originally prepared by a Subcommittee on Pyrometry consisting of Kirtland Marsh, Chairman; R. P. Brown, F. A. Faust, S. C. Horn, W. T. Morgan and C. O. Fairchild. The article on optical and radiation pyrometry was originally prepared by F. H. Dike. All of the material on pyrometry has been revised for this Edition by a Subcommittee consisting of R. B. Sosman, Chairman; P. H. Dike, W. G. Martin, F. W. Paine, W. F. Roeser and H. T. Wensel.

used intermittently up to a temperature of 2400°F. Its emf. is subject to change when the wires are exposed to a reducing atmosphere.

The iron-constantan thermocouple is not recommended for continuous use in air at temperatures above 1400°F. At this temperature, No. 8 gage wire of either element of the couple will last about 1000 hr. in air. The couple will generally have a longer life and be more satisfactory than Chromel-Alumel in a reducing atmosphere up to 1800°F.

The copper-constantan thermocouple is satisfactory for continuous use up to 700°F. and for intermittent use up to 1000°F.

The life of any base metal thermocouple will be relatively short when exposed continuously to temperatures above 2200°F. Alternately reducing and oxidizing conditions are especially detrimental to any base metal thermocouple.

Construction of Couples—The hot junctions of all thermocouples should be welded except in the case of base metal thermocouples for use at comparatively low temperatures (below 1000°F.), when the hot junction may be silver soldered. Borax is a satisfactory flux for silver soldering any base metal thermocouples or for welding iron-constantan. Fluorspar is better for Chromel-Alumel thermocouples. Plenty of flux should be used.

Use an oxy-gas or oxy-hydrogen flame and no flux for welding platinum thermocouples. Greater mechanical strength at the hot junctions of base metal thermocouples can be obtained by twisting the two wires together for about two turns before making the weld.

When base metal thermocouples have burned out or have become so contaminated that they give too low readings, destroy them so that they can not be used again by mistake.

When platinum thermocouples have become contaminated and give incorrect readings, it is often possible to do something toward their restoration by annealing with an electric current in air and cleaning with fused borax. Silicon, calcium, magnesium, and perhaps other elements, can be removed in this way, but iron can never be completely removed. The necessary equipment and procedure for reconditioning platinum thermocouples is described in Bureau of Standards Technologic Paper No. 170. It has recently been found that movement of the rhodium in the alloy is responsible for some of the change, and there is no remedy for this type of deterioration.

Cold Junctions—Every thermoelectric pyrometer is calibrated for a particular cold junction temperature, generally 0°F., 32°F., or 75°F. During subsequent use the cold junction need not necessarily be maintained at that particular temperature as long as the actual temperature is known, for it is possible to compensate for the difference between the actual cold junction temperature and that for which the instrument was calibrated.

It is generally more practical to compensate instrumentally for different cold junction temperatures than to maintain them at the particular temperature for which the pyrometer was calibrated. However, it is highly desirable to eliminate frequent variations in the cold junction temperature.

Extension Leads—Unless the two wires forming the thermocouple are long the cold junctions will be so close to the furnace that they will be subject to extensive temperature variations. As it is desirable to locate the measuring instrument some distance away from the furnace, and as it is often impractical to make the thermocouple long enough to reach to the instrument, lead wires or "extension leads" are used to connect the thermocouple to the instrument.

If in Fig. 1 the leads are of copper, the cold junction is close to the furnace at A. If, on the other hand, the extension leads consist of a pair of wires of the same material as the thermocouple, or of some less expensive pair of materials having the same thermoelectric characteristics as the thermocouple pair, the cold junction will be located not at the furnace but at the binding posts of the instrument, B, a position of more constant temperature.

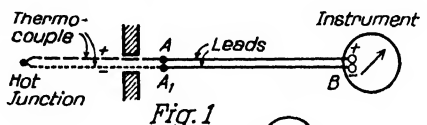


Fig. 1

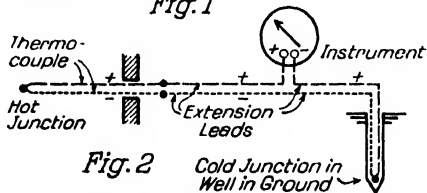


Fig. 2

Fig. 1—Simple thermoelectric pyrometer circuit.

Fig. 2—Thermoelectric pyrometer with the cold junction in a well in the ground.

The extension leads of base metal thermocouples are usually made of the same materials as the thermocouple wires, but in the case of platinum-platinum-rhodium thermocouples a copper lead is connected to the platinum-rhodium wire and a special copper-nickel lead to the platinum wire. Although the temperature-emf. relation of the copper, copper-nickel extension lead wire is practically the same as that of platinum-platinum-rhodium thermocouples, the individual lead wires are not identical thermoelectrically with the thermocouple wires to which they are attached and, therefore, the two junctions where the leads are attached to the thermocouple should be kept at the same temperature. This means that special care must be taken that this pair of junctions is not heated unsymmetrically. Such precautions are unnecessary in the case of base metal thermocouples where each lead and thermocouple wire to which it is attached are the same material. For similar reasons, the point of connection between the extension leads and thermocouple should be limited in temperature to 200°F.

Extension leads for a thermocouple of one pair of materials should not be used with a thermocouple of a different pair of materials.

The positive and negative lead wires, identified by color of insulation or otherwise, must always be connected respectively to the positive and negative elements of the thermocouple. If in doubt as to the identity of the positive and negative wires of extension leads, test them with a millivoltmeter or potentiometer. It is possible to have the extension leads wrongly connected to the thermocouple and also wrongly connected to the instrument, in which case the instrument will read up-scale, yet read wrong. An up-scale reading is no guarantee of correctness in the set-up. A safe way to connect the circuit is first to connect the leads alone to the instrument, twist the other end of the leads together and heat with a match. The instrument should read up-scale. Then connect the leads to the thermocouple, let the lead terminals cool, and heat the couple junction. The instrument must again read up-scale; if it reads down, reverse leads at the couple, not at the instrument.

There are a few simple methods of using extension leads to remove the cold junction to a position of constant temperature and for making one cold junction serve several thermocouples.

The arrangement shown in Fig. 1 with extension leads to remove the cold junction to the indicator, is the simplest, but the cold junction is still subject to the variations in room temperature, which will introduce errors in the reading unless the indicator is equipped with an automatic cold junction compensator.

Fig. 2 shows extension leads used to locate the cold junction in a well in the ground. This is a construction now seldom used but it serves to illustrate conveniently the character of the thermocouple circuit. The cold junction well consists of a piece of pipe with a pointed plug welded into one end to aid in driving it into the ground. If the well is 8 ft. deep or more and located away from steam and water lines, sewers, and furnace flues, the temperature at the bottom will be practically constant from day to day even though it may change a little with the season of the year.

In any pyrometer system the thermocouple and leads must be kept dry. The cooler temperature at the bottom of a cold junction well may cause moisture to condense in the pipe so that it is advisable to use an inner pipe in the well. The inner pipe should be capped or welded closed at the bottom end and the top end sealed with paraffin or compound.

The arrangement shown in Fig. 2 can be easily understood by considering a closed thermoelectric circuit without any measuring instrument. The positive and negative elements of the couple and the positive and negative extension leads are joined together at the hot and cold junctions respectively, and then, at any point along its length, the positive lead is cut so that the instrument can be connected in series with the two junctions. It should be noted that although both wires connected to the instrument are of the positive material, the one connected to the positive binding post on the instrument is connected to the positive element of the thermocouple and the one connected to the negative binding post leads ultimately to the negative element of the thermocouple. The same emf. reading would be obtained if we were to cut the negative lead for insertion of the instrument.

Cold Junction Compensation—If the cold junction temperature is not maintained constant, but is allowed to take the temperature of the air, as it is in most pyrometer installations, correction or compensation must be made for this fluctuating temperature.

If the measuring instrument (see later paragraphs for description) has no

manual or automatic device for compensating for the cold junction temperature, the correction can be made with the aid of tables of emf. vs. temperature for the thermocouple which is being used. It is incorrect simply to add an air temperature correction to the reading of the instrument without knowing the temperature-emf. curve.

With a millivoltmeter having no automatic cold junction compensation but with a scale reading in degrees, variations in the cold junction temperature can be compensated for by making the zero or open circuit position of the instrument pointer on the scale agree with the actual cold junction temperature. This can be done by means of the "zero adjustment" provided. This adjustment should be checked at frequent intervals because the cold junction temperature may have changed, or the zero setting of the pointer may have been accidentally disturbed.

With a millivoltmeter equipped with an automatic cold junction compensator, the zero position of the pointer should agree with a specified temperature on the scale or with the actual cold junction temperature, depending upon whether the compensator is electrically operated or is mechanically operated as in the case of the bimetallic spring, "Breguet Spiral," on the moving coil. In either case, follow the manufacturer's instructions.

With a potentiometer, a manually operated or an automatic cold junction compensator is generally provided. If it is manually operated, the dial should be adjusted to agree with the actual cold junction temperature at frequent intervals.

The temperature sensitive element of the compensator and the cold junction of the thermocouple should be kept close together and so shielded or wrapped that the temperature of the one will always be the same as that of the other. The reader is referred to the manufacturers for detailed descriptions of the different types of compensators in common use.

Fig. 3 illustrates the use of extension leads when a number of thermocouples are connected to a distant instrument equipped with an automatic cold junction compensator. Instead of extending the extension leads from each thermocouple all the way to the instrument, they are extended only to a centrally located common zone box and a single auxiliary couple is extended from the common zone box to the temperature sensitive element of the automatic cold junction compensator. The cold junction for the system is at B.

This arrangement is solely for the purpose of reducing the amount of extension leads required and is advantageous only when it results in a reduction in the total cost of installation.

Relation of Emf. and Temperature—Until recent years, each manufacturer of thermoelectric pyrometers had his own source for thermocouple alloys and his own curve for the relation of emf. to temperature. The platinum metal thermocouples were the first to be standardized, and tables of emf. vs. temperature for both the 10% rhodium and the 13% rhodium couple have been accurately determined by the National Bureau of Standards. These tables are now accepted as standard by most if not all of the manufacturers of pyrometers in the United States.

Next came Chromel-Alumel. These two materials are trade marked nickel alloys. Their composition and properties are capable of being kept under good technical control. The Bureau of Standards, having found that the alloys can be reproduced to specifications, has published a standard table which is now in general use by the pyrometer manufacturers.

Iron-constantan and copper-constantan are not yet standardized. Constantan is no longer a trade marked name, but applies to a limited range of copper-nickel alloys containing a little manganese. Pure iron is difficult to make, and the wire

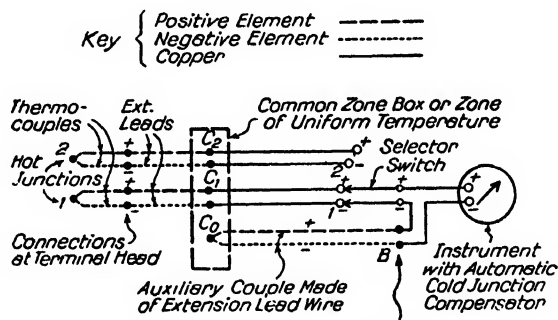


Fig. 3

Keep These Cold Junctions Close to the Temperature Sensitive Element of the Automatic Cold Junction Compensator

Fig. 3—Connections between several thermocouples and a distant instrument equipped with an automatic cold junction compensator.

actually used is about 99.9% iron with small amounts of various elements which influence its thermal emf. There is no difficulty about getting reproducible pure copper, but a minor complication arises from the fact that slightly different constantan alloys have been used with copper and with iron. Recent studies at the Bureau of Standards on the constantan group of thermocouple alloys have shown that the L. H. Adams' table for copper-constantan represents reproducible material, and that this same constantan can be combined with a low metalloid iron wire to give an emf. curve reproducible to 0.8%. Certain pyrometer manufacturers use constantan alloys that depart from this curve by several per cent, but they use other trade names for their couples so no confusion is likely to result.

Table I contains the accepted data for the platinum alloy and Chromel-Alumel couples, together with those data for constantan couples which the Bureau of Standards considers most representative of materials readily available. At the head of each column, in naming the couple, the positive element is named first.

Table I
Representative Tables of Emf. vs. Temperature for the Principal Commercial Thermocouple Combinations. Emf. is in Millivolts. Cold Junction, 32°F.

Temp., °F.	90 Pt, 10 Rh vs. Platinum ^a	87 Pt, 13 Rh vs. Platinum ^a	Chromel vs. Alumel ^b	Iron vs. Constantan ^c	Copper vs. Constantan ^c
32	0	0	0	0	0
100	0.221	0.220	1.52	2.00	1.52
200	0.594	0.596	3.82	5.03	3.97
300	1.016	1.030	6.09	8.12	6.64
400	1.473	1.503	8.31	11.24	9.52
500	1.956	2.012	10.56	14.35	12.57
600	2.457	2.546	12.85	17.43	15.77
700	2.975	3.102	15.18	20.48	19.09
800	3.505	3.675	17.52	23.53	22.53
900	4.044	4.263	19.88	26.59	26.06
1000	4.594	4.867	22.25	29.70	29.67
1100	5.155	5.486	24.62	32.88	....
1200	5.725	6.122	26.98	36.17	....
1300	6.307	6.773	29.33	39.58	....
1400	6.898	7.438	31.65	43.12	....
1500	7.500	8.118	33.94	46.74	....
1600	8.112	8.810	36.20	50.39	....
1700	8.734	9.518	38.43	53.87	....
1800	9.365	10.237	40.62	57.16	....
1900	10.006	10.970	42.77	....	....
2000	10.657	11.720	44.89	....	....
2100	11.315	12.478	46.97	....	....
2200	11.977	13.242	49.01	....	....
2300	12.642	14.010	51.00	....	....
2400	13.305	14.777	52.95	....	....
2500	13.968	15.543	54.85	....	....
2600	14.629	16.308	....	....	....
2700	15.288	17.073	....	....	....
2800	15.943	17.833	....	....	....
2900	16.596	18.588	....	....	....
3000	17.246	19.342	....	....	....

^aBur. Standards RP 530 (1933). ^bBur. Standards RP 767 (1935). ^cBur. Standards RP 1080 (1938).

Other Thermocouples—Many other combinations have been used in thermoelectric pyrometry, but none has attained the general acceptance of those listed in Table I. The use of iron-chromium-nickel alloys has already been mentioned. Molybdenum vs. tungsten is useful at very high temperatures in hydrogen or vacuum. Graphite vs. tungsten and graphite vs. silicon carbide have been given some trials in open hearth steel furnaces and ladles.¹

Protection Tubes—One of the reasons why certain materials have come into common use for thermocouples is that they are reasonably stable thermoelectrically when heated in a clean oxidizing atmosphere. The standards of performance which are generally accepted for the various combinations of thermocouple materials are based upon their performance in air. Although it has not been shown that a reducing atmosphere, in itself, necessarily contaminates or alters the thermoelectric properties of thermocouple materials, it is nevertheless generally observed that exposure

¹See G. R. Fitterer, A New Thermocouple for the Determination of Temperatures Up to at Least 1800°C., *Trans., A.I.M.E.*, 1933, v. 105, p. 290.

of thermocouples to such atmospheres is accompanied by contamination or change in the chemical composition which seriously alters their thermoelectric properties. In order, then, to obtain the best performance of thermocouples, it appears necessary to maintain them in an atmosphere having essentially the same composition as air. Consequently the selection of a proper protection tube, which will protect the thermocouple from vapors, fumes, or furnace gases, is sometimes as important as the selection of the thermocouple materials.

Contamination results from causes such as the following:

(1) Metals (solid, liquid, or vapor) coming into contact with the thermocouple materials and altering their chemical composition.

(2) Furnace gases and fumes coming into contact with the thermocouple materials. Sulphur and sulphur compounds are particularly deleterious.

(3) Materials normally stable in an oxidizing atmosphere coming into contact with the thermocouple material in a reducing atmosphere. One common cause of contamination, which is serious in the case of rare metal thermocouples, is the reduction of silica (usually present in insulating and ceramic protection tubes) to silicon which readily combines with the thermocouple materials.

(4) Preferential oxidation and reduction of base metal alloys when these are exposed alternately to oxidizing and reducing atmospheres. This results in a gradual change in chemical composition, because all the elements which comprise an alloy cannot be expected to oxidize and reduce at the same rates under all conditions.

Many types of protection tube are required in order to meet all needs. In many cases, the conditions under which thermocouples are used are such that two tubes are required to provide the desired protection. For instance, a primary tube of porcelain or fused silica may be placed inside of a secondary tube of metal, silicon carbide, or fire clay. The primary tube of low volatility is intended to provide the imperviousness to gases at high temperatures, and the secondary tube provides the resistance to thermal and mechanical shocks and to corrosion.

In thus providing protection for the thermocouple, however, one should not lose sight of the fact that a thermocouple can perform its function only when the conditions of heat transfer are such that the measuring junction will attain or at least approximate the temperature to be measured. When a tube of large cross section or more than one tube is used, particularly if the tubes have a high thermal conductivity, it should be carefully considered whether the depth of immersion is sufficient to insure that the temperature of the thermocouple junction is reasonably close to the temperature to be measured. Short heavy tubes may cool the junction so much that the indications are comparatively worthless.

Platinum to platinum-rhodium thermocouples are particularly susceptible to contamination and should be protected by ceramic tubes which are impervious to gases and vapors at all operating temperatures. If furnace gases are not present, metal protection tubes are usually sufficient protection for base metal thermocouples. The oxide coatings on the thermocouple wires are fairly effective in protecting the wires from contamination by metallic vapors. Metal tubes which provide sufficient protection in an oxidizing atmosphere may be entirely unsatisfactory if large amounts of furnace gases are present.

The primary ceramic tubes which meet most requirements of stability and imperviousness to gases are: Highly refractory porcelain, sometimes called "Sillimanite" or "Mullite," for temperatures up to 2800°F. Fused silica for temperatures up to 1900°F. in an oxidizing atmosphere. Pyrex glass for temperatures up to 1100°F.

The secondary or metal tube most suitable for a particular application depends to a large extent upon the type of corrosion encountered. Nickel tubes are useful above 2100°F. Tubes of nonscaling alloys such as nickel-chromium and nickel-chromium-iron are suitable for many applications at temperatures up to 2000°F. Tubes of iron and steel are suitable for numerous applications up to 1500°F. Calorized wrought iron is impervious to certain gases and meets certain needs up to 1800°F. Fire clay, silicon carbide, and graphite meet certain requirements of secondary tubes at temperatures above the useful limit of metal tubes.

Numerous other types of secondary tubes have been developed for specific purposes. Information regarding the best type of tube for any particular purpose is usually available from the pyrometer manufacturer.

Insulators—Except at the hot junction where the two wires should be welded together the two elements of a thermocouple must be electrically insulated from each other. Fire clay or porcelain beads and even asbestos for low temperatures, are satisfactory for base metal thermocouples. However, for platinum thermocouples, clean porcelain beads or tubing should be used.

The insulation on the thermocouples should be maintained intact because if the wires come in contact with each other another junction may be formed which will cause the indicator to register some other temperature than the temperature of the hot junction of the thermocouple.

Terminal Heads—Terminal heads for thermocouples are not absolutely necessary because the leads can be soldered, brazed, or welded directly to the elements of the thermocouple, but they simplify installation and replacement of thermocouples, keep contaminating dirt and dust out of the protection tube and provide a good connection between thermocouple and leads. It is recommended that they be used.

Measuring Instruments—The instrument for measuring the emf. of the thermocouple may be either *indicating* or *recording*. Either an indicating or a recording instrument may also act as a *controller*.

An indicating pyrometer simply shows the instantaneous temperature on a dial. A recording pyrometer produces a graphic record of the temperature on a moving sheet of paper graduated in minutes, hours, or days. Such a record serves to show whether the furnace has been maintained at the proper temperature at all times. A graphic record of the temperature is of particular value for manual control, in that it shows the trend or the rate of change in temperature and so enables the operator to anticipate conditions and to control the furnace more intelligently. Graphic charts filed away are often of value at some later date when a question arises as to the quality of materials produced on a certain day.

Most indicators and recorders can be grouped in two general classifications: (1) millivoltmeters or deflection type instruments, and (2) those operating on the potentiometer principle. In addition, there are some that embody features of both types.

Millivoltmeters—A millivoltmeter consists of a coil of wire suspended between the poles of a permanent magnet so that the coil is free to move. A pointer is attached to the coil and moves over a scale graduated in millivolts or in degrees. The terminals of the thermocouple are attached to the terminals of the coil, and the emf. generated in the thermocouple circuit sends a current through the coil, causing it to deflect in the magnetic field. The magnitude of the deflection depends upon the current through the coil which in turn depends on the emf. generated by the thermocouple and the resistance of the circuit.

Millivoltmeters are calibrated to indicate temperature correctly when connected to a thermocouple and leads of a certain total resistance. The indications of the instrument will change if the resistance of thermocouple plus leads is other than that specified on the instrument. In principle, inaccuracy in a millivoltmeter pyrometer due to changes in the thermocouple can be corrected, at least over a reasonable range near the critical operating temperature, by adjusting the resistance of the circuit, a simple method of adjustment which is possible only in the case of millivoltmeter type instruments. Rheostats for this purpose are seldom provided, however, and this method of correction is not recommended as a standard procedure.

Since the design of a millivoltmeter is a compromise between sensitivity, ruggedness, and resistance, no specific recommendations as to the proper value of internal resistance can be made. However, it is safe to say that much less than 100 ohms will probably make the instrument subject to appreciable errors with change in temperature and that much over 600 ohms will probably require that the instrument be more delicate than is necessary.

Potentiometers—A potentiometer, shown diagrammatically in Fig. 4, is a source of known values of emf. against which the unknown emf. from a thermocouple may be balanced. The primary source of the emf. may be a dry cell, a liquid primary cell, or a storage cell. The dry cell is the most used.

The standard current to make the drop in emf. across the fixed resistance of the slide wire agree with the millivolt scale attached to it is obtained by adjusting the rheostat until the emf. drop across the standard cell coil is equal to the emf. of the standard cell, as indicated by a zero deflection of the galvanometer with the switch on the standard cell point. This

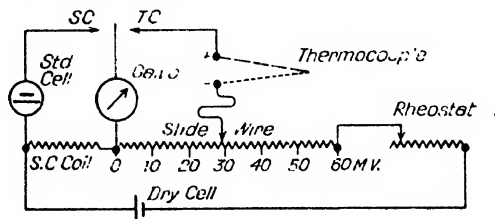


Fig. 4—Diagram of potentiometer circuit.

adjustment needs to be made at frequent intervals because the voltage of the dry cell or other current source constantly changes.

The emf. from the thermocouple is then balanced against the emf. drop across a portion of the slide wire by adjusting the position of the movable contact until the galvanometer deflection is zero.

The galvanometer, like the millivoltmeter, is essentially a movable coil between the poles of a magnet, but is usually capable of detecting smaller variations of current. It has no measuring function, such as the coil has in the millivoltmeter, but acts solely by deflecting from its zero position. The measuring is all done by the moving contact on the slide wire.

The standard cell is the source of known constant emf. It has practically no current capacity so its terminals should never be connected together except through a resistance of several thousand ohms. A standard cell may be badly damaged if subjected to temperatures below 0°F. or above 120°F. It undergoes small permanent changes of the order of 0.01-0.1% at temperatures below 40°F., and it is therefore desirable not to expose it to temperatures below freezing.

The reading of a potentiometer pyrometer is independent of the resistance of the thermocouple circuit except as an increase in the resistance will decrease the sensitivity of response of the galvanometer. The higher the resistance of the thermocouple circuit the greater is the change in emf. required to produce a perceptible deflection of the galvanometer. It is therefore advisable to keep the resistance of the thermocouple circuit or length of extension leads within reasonable limits. This is particularly true in the case of a recording potentiometer where an appreciable deflection of the galvanometer pointer is required to operate the automatic balancing mechanism.

Since only the response of the galvanometer is affected by a change in resistance of the thermocouple circuit, a potentiometer cannot be adjusted to correct for variations from the standard emf. of a thermocouple by changing the resistance of the thermocouple circuit. By increasing or reducing the value of the standard current through the slide wire by the same percentage that the emf. generated by the thermocouple is above or below the standard emf. for that type of thermocouple, the reading of the potentiometer will be corrected for the discrepancy in the emf. This adjustment is practical only when the potentiometer is equipped with a scale to indicate the percentage deviation from the standard value of the current through the slide wire and is applicable only to a potentiometer connected to a single thermocouple.

In general, it is advisable to replace the thermocouple rather than tamper with the indications of the instrument.

Portable Potentiometer—The adjusting mechanism for the moving contact of the slide wire of a potentiometer may be either manual or automatic. Manual adjustment is found in various types of *portable indicating potentiometer*. These instruments can be made rugged and are little subject to change in calibration and are, therefore, satisfactory for use with a standardized thermocouple for calibrating other thermoelectric pyrometers. Their cold junction compensation is always electrical, consisting of supplementary coils that can be connected in series with the slide wire, and the compensation adjustment is usually manual. For a particular type of thermocouple, such as the Chromel-Alumel, the compensation may also be made automatic, and consists then of supplementary coils of a metal whose resistance changes at the proper rate with the temperature of the instrument.

The portable indicating potentiometer may be used with any type of thermocouple if the main dial is calibrated in millivolts and if it is provided with a manually operated cold junction compensator calibrated in millivolts.

The main dial and the compensator dial can be calibrated in degrees of temperature for a particular type of thermocouple but both dials should also be calibrated in millivolts if the instrument is to be more generally useful.

Automatic Potentiometer—In the past 20 years there has been an extensive development of the automatic potentiometer. In this instrument the galvanometer, on deflecting from zero, actuates a motor mechanism of some kind which adjusts the slide wire contact until the galvanometer deflection is again zero. In one group of instruments the galvanometer coil carries a pointer, like that of the millivoltmeter, and this pointer interferes mechanically with a mechanism having a periodic motion. In another group the pointer is replaced by a mirror and a reflected beam of light which acts in various ways through a photoelectric cell as a medium.

In most automatic potentiometers the standard current in the slide wire must

be adjusted manually with the aid of the standard cell. In a few types this adjustment, also, is made automatically at regular intervals. One type records the actual value of the slide-wire current at fixed intervals, thus making the record complete even though the adjustment may have been neglected. In one type dependence is placed upon the constancy of characteristics of a small ammeter, in place of the standard emf. cell.

Installation of Thermoelectric Pyrometers—Thermocouples—Locate the hot junctions of the thermocouples where they will measure the desired temperature. Close up the openings around the protection tube to prevent hot gases from blowing out around the terminal head and to keep cold air from being drawn in around the thermocouple.

Make the opening in the furnace large enough so that a second thermocouple may be inserted alongside the furnace thermocouple for calibrating purposes but keep the extra space plugged up when not in actual use.

Determine the proper depth of immersion and mark the thermocouple or protection tube or both so that they can always be returned to the same position. It is well to have the thermocouple clamped in the protection tube and the protection tube clamped to the furnace so that the depth of immersion cannot be changed accidentally.

Be sure that positive leads are always connected to positive leads or the positive element of the thermocouple, and negative to negative except at the hot junction. If a positive lead has been erroneously connected to a negative, a thermo junction will have been formed which will cause a deflection of the instrument pointer when the junction is heated. Any suspected splices or connections can be tested in this way.

It is generally worth while, although not absolutely necessary, to install the leads from the thermocouple to the instrument in conduit.

All connections in the thermocouple circuit, except where binding posts are provided, should be soldered. Insist that the soldering be done with a soldering iron rather than with a torch. A poor joint made with an iron is generally apparent, whereas a torch made joint may appear to be good and still be poor.

Because of the alloys used, some extension leads are difficult to solder, and it may be necessary to scrape and tin each individual strand in order to assure that all strands are well soldered together. All strands must be well soldered.

Never use soldering acid as this may set up galvanic action and cause serious errors in the readings. Lump or powdered rosin or a solution of rosin in alcohol is the best for copper, but is not satisfactory for most extension lead material. A good soldering paste can be used if the joint is well washed with gasoline (or better, carbon tetrachloride which is noninflammable) after the soldering is completed.

Disconnect all instruments before ringing out any circuits with a battery or magneto and bell, because the instruments are not built to stand even battery voltage.

In a millivoltmeter installation, measure and record the resistance of each thermocouple circuit to make sure that it agrees with the manufacturer's specifications. A comparison of these records with subsequent measurements may reveal the source of some trouble.

Instruments—For the greatest return on the investment, locate the recorder where the furnace operator can observe it and make use of the information it gives.

The principal enemies of the indicating and recording instruments are: (1) Dust, (2) vibration, (3) excessively high temperatures, (4) excessively low temperatures. The instrument should be mounted on a substantial support as free from vibration as possible and so located that it will not be mechanically damaged, nor subjected to currents of air, direct radiation from the sun or hot surfaces, or extreme variations in temperature. A special pyrometer booth is often advisable.

Measurement of Temperatures with Thermocouples—A thermocouple measures only the temperature of its hot junction. Since a thermocouple has appreciable mass, time is required for the temperature of the hot junction to change. In a furnace whose temperature is changing, a thermocouple will indicate a temperature lower or higher than the actual temperature of the furnace depending on whether the latter is rising or falling. This is called temperature lag. The extent of such lag will depend upon the mass of the thermocouple and protection tube around it and upon the rate of change of furnace temperature.

Heat may be conducted to or away from the hot junction from a hotter or to a colder portion of the thermocouple and so cause the temperature of the hot junction to differ from that of the medium immediately around it. If the depth of immersion of the thermocouple in a furnace, that is, the length of that portion

within the furnace chamber, is insufficient, heat will be conducted away from the hot junction and reduce its temperature below that of the medium around it. To correct such a condition, increase the depth of immersion of the thermocouple in its protection tube an inch or two at a time until the pyrometer shows no further increase in temperature. During this procedure the furnace temperature must be maintained constant by means of another stationary thermocouple, or otherwise, and sufficient time must be allowed for the temperature of the hot junction of the thermocouple to reach equilibrium. The error in indication of furnace temperature by a thermocouple with insufficient depth of immersion will not necessarily be a constant error but may vary from hour to hour and day to day and so cannot be determined and allowed for in subsequent readings. It is better to buy a thermocouple longer than necessary than to have too little depth of immersion.

Flame in contact with the hot junction will cause the thermocouple to indicate a temperature higher than the average furnace temperature, and flame in contact with any part of the thermocouple may cause high readings and will certainly shorten its life. Contact with flame may frequently be avoided by inserting the thermocouple through a hole in the rear or a side wall rather than through the arch.

The temperature of material in a furnace can sometimes be estimated by comparing the brightness of the material with that of the hot end of the thermocouple. Have the hot end of the thermocouple as close to the work as possible and in such a position that both can be observed through a peek hole in the door. Be sure that neither work nor thermocouple are licked by any flame and that light from a hot flame-licked surface or combustion chamber does not cause either to appear hotter than it really is. When the work and hot junction are of equal brightness as closely as can be determined by eye, the temperature of the two will be the same to within possibly $\pm 10^\circ\text{F.}$, provided that both have dull absorbent surfaces which will not reflect light from hotter walls or flame.

Pyrometer Troubles—Pyrometer troubles can be divided into two classes, those external to and those within the instrument.

The details of design of instruments in use today are so varied that it is impractical to attempt a discussion of possible troubles within the instruments themselves. Some instruments are sealed by the manufacturer and in case of trouble within the case of these instruments they should be returned to the manufacturer for repair.

Other instruments, particularly recording and some control instruments, require occasional cleaning or adjustment by the user and accordingly those parts are made accessible. A book of instructions is furnished by the manufacturer with such instruments, so in case of trouble, consult the instruction book and proceed as directed. If the trouble cannot be eliminated, consult the manufacturer. In some instruments unit parts such as galvanometer systems and selector switches can be removed from the instrument and returned to the manufacturer, thus eliminating the necessity of returning the entire instrument.

Troubles external to the instrument can generally be eliminated by the user if the cause of the difficulty can be located. The following paragraphs enumerate some of the troubles which may be encountered and tell how to locate them.

I. Instrument Does Not Respond Properly to Change in Temperature of Thermocouple—(a) *Burned Out Thermocouple*—One element of the thermocouple may be completely oxidized or broken. This should be apparent from examination.

(b) *Broken Connection*—A wire may have come loose from a binding post or one of the leads may have broken at a soldered connection or elsewhere. The first should be apparent from a visual examination but the second may require that the instrument be disconnected and the circuit rung out with a battery or magneto and bell. If the circuit external to the instrument is found to be complete and the thermocouple in good condition there may be an open circuit in the instrument. This can be checked by applying an emf. from a potentiometer or another thermocouple to the binding posts of the instrument in question. Check all battery connections and sliding contacts. If the trouble is definitely located in the instrument, call in the manufacturer or return the instrument to him.

(c) *Faulty Selector Switch*—If a selector switch is used, the trouble may be in the switch in which case the instrument should respond properly when the thermocouple leads are connected directly to the instrument.

(d) *Short Circuit*—Make sure the leads or thermoelements have not become short circuited in the terminal head of the thermocouple. A short circuit may exist between the instrument and thermocouple. Disconnect the instrument and thermocouple and ring out the circuit which should be open.

II. Instrument Reading Is Erratic—The reading of the instrument may vary up and down the scale or if a selector switch is used the instrument may show one reading at one time and a different reading at another even though the furnace temperature has not changed.

(a) *Loose Connection*—Make sure that all binding posts and other connections are tight, that all sliding contacts are clean, and that the thermoelements are not loose or broken at the weld or elsewhere. If the weld at the hot junction is suspected, pinch it with a pair of pliers while it is still hot and note if the instrument reading changes suddenly. The leads may be broken at some point and still make intermittent or poor contact, in which case pulling or shaking the leads may locate the defect.

(b) *Faulty Selector Switch*—The switch contacts may be poor due to dirt or loose parts and this should be revealed by operating the switch. Tighten all parts, clean thoroughly, and if the contacts appear to have been greased supply a thin coating of fresh vaseline. If the switch is completely enclosed, not built for ready opening, a service man should be called or the instrument returned to the manufacturer.

(c) *Fault in Instrument*—Test for an open circuit in the instrument as described in Section I (b). In the case of a millivoltmeter the instrument pointer may be dragging on the scale. Some part of the moving system, or in the case of a potentiometer some part of the galvanometer such as the coil or a fiber of insulation on the coil, may be making contact with some part of the instrument, or a loose piece of magnetic material on one of the magnet poles. Rap the instrument case sharply with the knuckles and note if the pointer jumps to another position and remains there. It is sometimes possible to dislodge the obstruction by repeatedly causing the pointer to deflect clear across the scale. This can be done by intermittently connecting the instrument to a potentiometer or to a thermocouple hot enough to cause full scale deflection.

If the pivots of the moving coil of a millivoltmeter have become dull, there may be enough friction to cause the pointer to stop short of the actual temperature. Rapping the instrument case with the knuckles will generally cause the pointer to move to nearly the correct temperature. This trouble can only be corrected at the factory.

III. Instrument Reads Low—(a) *Zero and Cold Junction Settings*—Check the zero and cold junction settings as instructed by the manufacturer. If automatic cold junction compensation is provided, check the setting and adjustment of the compensator.

(b) *Battery Current*—If a battery is used in the measuring circuit, check the battery current.

(c) *Deteriorated Thermocouple*—The thermocouple may have deteriorated by oxidation or otherwise to such an extent that a lower than normal emf. is generated. Try a new thermocouple.

(d) *Wrong Thermocouple*—If a thermocouple which generates an emf. other than that for which the instrument is calibrated is connected to the instrument, it will read incorrectly; that is, a Chromel-Alumel thermocouple connected to an instrument calibrated for iron-constantan thermocouples will produce low readings.

(e) *Increased Lead Resistance*—Some of the individual wires in stranded leads may have broken or been poorly soldered or the thermocouple may be badly oxidized. Disconnect the instrument and measure the resistance of the external circuit. If it is materially higher than originally, replace the thermocouple and if still high look for trouble in the leads.

(f) *Short Circuit Through High Resistance*—A short circuit may be through low resistance, as in the case of good electrical contact between the two elements of the thermocouple or it may be through high resistance as in the case of a poor electrical contact between the elements of the thermocouple or leads. If the first case, the instrument reading will be much lower than the actual temperature, while in the second case the reading may be only a little lower than the correct temperature. Examine the thermocouple and all readily accessible points where such a condition might exist. If this fails, disconnect the thermocouple and instrument and measure the resistance which should be infinitely high. If an ohm meter is not available, try ringing through from one lead to another with a magnet.

A high resistance short circuit may be caused by dampness of the insulation on the leads. Moisture on some insulating materials may set up a galvanic action and cause the instrument to read too high. The previous use of soldering acid may cause the same effect.

(g) *Fault in the Instrument*—The calibration of the instrument may have changed. This can only be determined by a recalibration as described later.

A high temperature around the instrument would tend to make the instrument read low but generally not enough to be detected except by a recalibration.

If dry batteries are used in or around the instrument, moisture on the paper covers may cause a high or low reading. Note if the reading changes when the batteries are separated from each other and insulated from their support with a piece of glass.

IV. Instrument Reads High—(a) *Zero and Cold Junction Settings*—See Section III (a).

(b) *Faulty Standard Cell*—If the standard cell in a potentiometer has been damaged or has deteriorated, its voltage may be low and a low value of the standard current in the potentiometer circuit will result. This will cause the instrument to read high. Try another standard cell. Never test a standard cell with a voltmeter.

(c) *Wrong Thermocouple*—See Section III (d). A 13% alloy platinum-rhodium thermocouple connected to an instrument calibrated for 10% alloy platinum-rhodium thermocouples will produce a high reading.

Recalibration of a Thermoelectric Pyrometer—Comparison Method—The most satisfactory method of checking the calibration of a thermoelectric pyrometer is by comparison with another thermoelectric pyrometer of known accuracy such as a portable indicating potentiometer and a calibrated thermocouple. It is well to have two calibrated thermocouples, one to be kept as a primary standard and used only for rechecking the calibration of the second which is used for checking the calibration of the furnace pyrometer.

During the calibration, the hot junction of the standard thermocouple should be maintained in intimate contact with the hot junction of the furnace thermocouple in order to assure that they will be at the same temperature. In the case of base metal thermocouples, it is often advisable to bind them together with wire which will not contaminate the couples and will resist the furnace temperature. Insert both thermocouples in the same protection tube, making temporary use of a larger tube if necessary so that both will be equally lagged. Do not try to calibrate a thermocouple in one protection tube with a standard couple in another tube. If both thermocouples cannot be inserted in the one protection tube, use a larger diameter protection tube or insert them in the furnace without any protection tube. Remember that a Chromel-Alumel thermocouple should not be subjected to a reducing atmosphere for any extended length of time. Platinum thermocouples should never be inserted in a furnace without a protection tube, not even during calibration.

Have the furnace thermocouple at the same depth of immersion as in use, for if the thermocouple is contaminated the error in the reading may vary with the depth of immersion.

During calibration, the furnace temperature should be maintained as nearly constant as possible, but it is generally better to have a gradual increase or decrease in temperature than to have the temperature rising and falling as is often the case in an automatically controlled furnace. Substitute manual control if possible, or else lag the thermocouples to such an extent that the fluctuations in furnace temperature do not affect the temperature of the couples.

After both thermocouples have come up to temperature equilibrium, comparison readings may be made. Take several readings on each instrument at intervals of several minutes to make sure that a steady state has been reached.

If the instrument is found to be in error, it may be owing to one of the conditions mentioned under "Pyrometer Troubles," Section III. "Instrument Reads Low," or Section IV. "Instrument Reads High." All of these possibilities should be investigated before it is concluded that the calibration has changed.

If it is definitely decided that the calibration has changed, the trouble may be in the thermocouple or in the instrument. Try a new thermocouple and if that does not improve the situation the trouble is probably in the instrument, in which case it will have to be returned to the maker or a correction applied to the reading.

The correction to be applied can be determined by calibration at several temperatures throughout the critical operating temperature range of the furnace. If this is not possible, determine the correction at one point by calibration and use a percentage correction at other temperatures, that is, if a correction of $+10^{\circ}\text{F.}$ at 1000° has been determined, use a correction of $+5^{\circ}$ at 500° and a correction of $+15^{\circ}$ at 1500° . These corrections may not be quite correct but they will be better than none.

Calibration by the Freezing Point Method.—This is the method used by the National Bureau of Standards and a few well equipped laboratories for making primary calibrations of thermocouples. The proper procedure involves considerable technique and careful attention to details, and except in a few limited cases is not recommended for the majority of pyrometer users. Those interested in this method of calibration are referred to "Bureau of Standards Technologic Paper No. 170," and to "Methods of Testing Thermocouples and Thermocouple Materials," Bureau of Standards Research Paper, RP768, 1935.

Automatic Temperature Controllers—It is beyond the scope of this article to discuss the application of automatic temperature control equipment or even to describe the many and varied mechanisms that have been applied to thermoelectric pyrometers to enable them to control as well as indicate and record temperature.

An automatic temperature controller consists of: (1) A measuring instrument such as a millivoltmeter or potentiometer with its thermocouple; (2) an operating mechanism such as a chopper bar, contactor, or relay, including in some cases the driving motor; (3) a fuel valve, or for electric furnaces a device for altering the current.

The principal types of controls in common use are: (1) On and off; (2) 2-position; (3) 3-position; (4) throttling (various kinds); (5) multiposition follow up; and (6) floating. This classification of the various kinds of control is based on the manner in which the heat supply is automatically adjusted in response to the departure of the temperature from the control point. The characteristic action of types 1 and 2 is alternately to change the heat supply to high and low values as the temperature oscillates about the control point, with the result that the normal record is a wavy line if the recorder is sufficiently sensitive to detect the changes. With the other types the heat supply is changed only when the departure from the control point has reached a definite value, depending upon the width of the so-called neutral zone of types 3 and 5, or the width of the dead zone or limit of sensitivity in types 4 and 6.

On-and-Off Control—This type requires the least expensive equipment and is most generally used for electric furnaces. The results obtainable are satisfactory in most cases if the pyrometer is sensitive, if the lag is not too great, if only small oscillations of temperature are permissible, and if the "on" value of the power is not too great for the temperature selected. In many cases where only one nonadjustable source of power is available it is selected to be adequate for heating up and is too great for best results when the furnace is up to temperature. However, pyrometers are available that will control to a few degrees under such conditions.

Two-Position Control—The same pyrometric equipment is used either for on-and-off or 2-position control. The only difference between the two types is that in 2-position control the heat supply does not shut off completely when the temperature is high. In the latter case, generally selected for gas or oil firing, the fuel valve and in some instances the air valve working with it are operated back and forth to adjusted high and low limits, selected according to variations in demand and heat supply which must be provided for. It is not necessary that the gas-air ratio of the valves be correct through the full range, but only at and near the limits selected. However, in this type it is sometimes difficult to maintain the furnace atmosphere within the narrow limits of composition required.

Three-Position Control—This type of control can be applied only with equipment selected for this purpose and not with the on-off or 2-position controllers. The minimum required for electric heating is: Two voltages or two heating elements; two contactors; and possibly two relays. In these instances the third "position" is all power off. There are two principal advantages of this type over on-off control. If it is necessary to control at a temperature well below the maximum attainable with all power on, then an intermediate setting will improve control. For continuous processes, however, where a high heat is not essential for heating up, the 3-position is little better, if at all, than 2-position, in accuracy of control. In this type of control the neutral zone is always fairly wide because if it is narrow the rising or falling temperature traverses it so rapidly that the effect is the same as 2-position control, and probably less accurate.

Throttling Control—Equipment for this type of control for fuel fired furnaces consists in holding the valves at the setting required for the temperature selected, moving them only when the temperature changes and then only enough to stop the change and bring the temperature back to the control point without hunting. By hunting is meant oscillation of temperature with throttling control. Special equip-

ment is, of course, necessary, and is selected only when the apparatus has a large heat capacity or is so designed that the temperature of the thermocouple will lag seriously.

Multiposition Follow-Up—This type of control can be described for the present purpose as 3-position control with the limits fairly narrow and means for shifting the neutral zone to take care of changes in heat supply or demand, and the principal adjustment has to do with the width of the neutral zone. Detailed instructions are generally provided for this type of controller.

Floating—This type of control is applicable only where the lag is small and where the heat supply and demand never vary rapidly. Ordinarily no adjustments are required. When properly applied the accuracy obtainable is comparable with that of 2-position control with the two valves of heat set close together, but generally lag is sufficient to noticeably decrease the ability to maintain the correct temperature.

Installing and Starting Up Controllers—It is important to mount the controllers in locations relatively free from vibration. Not only will the accuracy of control generally be improved, but in some cases the wear on the control equipment will be lessened. Vibration-proof mountings are available for all types.

In the original installation of a controller it is important to test it as an indicator or recorder before connecting the power for the control circuits and to see that it is indicating correctly. Having done this the control circuit may be completed and the power cautiously applied either by interposing a lamp or low capacity fuse temporarily in the circuit or by momentarily closing the power switch. It is now necessary to check the polarity of connections to see that heat is turned on for a low temperature and off for a high temperature, and with 3-position control that the intermediate heat is applied when the control point is moved to coincide with the indicated temperature. So far the tests can be readily made without actually turning on the heat, but by observing the operation of relays, contactors, or valves, except with suppressed scale instruments, in which case it is necessary either to move the indicating pointer or carriage up to the control point or to stand by until the lowest temperature on the scale has been reached. In any case during the first

heating up, it is important that the operator stand by until the temperature has reached the control setting to determine that the heat is properly turned off and that all signal and safety devices are correctly wired. It is not necessary to do all this checking at a high temperature, but it is nevertheless advisable to watch the controller until the desired temperature has been reached.

Control Circuit Wiring—Except in the simplest cases control circuits should be wired according to a diagram furnished by the manufacturer or carefully designed beforehand. While the circuits are not particularly complicated there are many different arrangements, only a few of which will be described here. All of these circuits

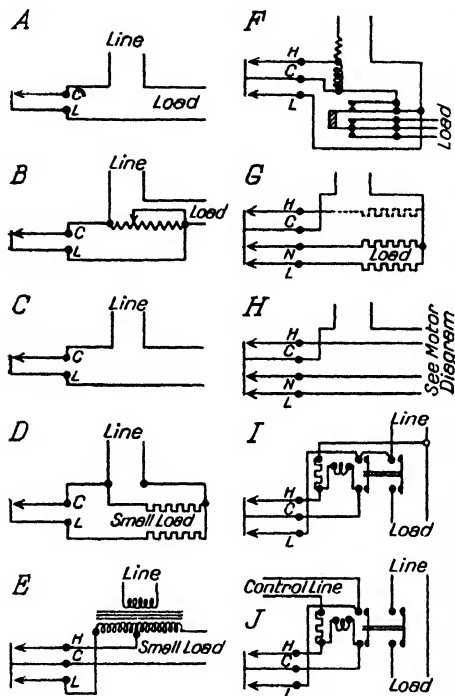


Fig. 5—Wiring diagrams for automatic control circuits. A. "On and off" controller for electric heater or solenoid valve, not for relay or contactor unless specified; B. 2-position controller with rheostat for small furnace; C. 2-position controller; D. 2-position controller with 2 heating units; E. 2-position controller with tapped transformer, "C" always on "H" or "L"; F. Principle of 2-position controller and 3-wire relay; G. Principle of 3-position controller connection; H. 3-position controller with reversing motor with a 3-position and limit switches; I. 2-position controller and 3-wire relay, common line; J. 2-position controller with 3-wire relay, separate control line.

have many features in common. It is general practice to mark one of the terminals with a *C* for "common." In the simplest case of on-off control there will be one other terminal marked *L* for "low" and when the temperature is low the controller closes a connection or contacts between *C* and *L*. These two terminals alone suffice not only for on-off control but 2-position control with a rheostat or double heaters in an electric furnace, or for the solenoid valve with adjustable limits. In many cases, however, a third terminal is required which is usually marked *H* for "high" and connection is made between *C* and *H* when the temperature is high. In some controllers, *C* is always connected to either *L* or *H* while in other controllers, *C* is disconnected when the temperature is at the control point, in which case we have a 3-position controller. However, for some types of circuits or controllers 3-position control requires the use of a fourth terminal which is usually marked *N* for "normal" and here contact is made between *C* and *N* when the temperature is within the neutral zone.

In practically all control circuits the terminal *C* is connected permanently to the line or to the load or in case 3-wire relays are used, to one terminal of the relay coil as shown in the diagrams. Generally the control terminals are not connected to anything but switch or relay contacts within the instrument. The contacts are generally rated for not more than 250 volts and current capacity according to specifications. If there is any uncertainty about the contact capacity not more than 50 or 100 watts should be risked. When relays are used between the controller and a magnetic contactor or motor valve it is preferable to use the 3-wire type sometimes called "hold in," "mechanical latch," or "thermostat" relay, the opening of which requires that a contact be closed, for example, *C-H*. The wiring diagrams in Fig. 5 are typical and are given as an illustration, but should not be used in place of those furnished by the manufacturer excepting in the simpler cases unless such circuits are familiar.

Optical and Radiation Pyrometry

Introduction—Where a thermocouple cannot be used for the measurement of high temperatures, some form of optical or radiation pyrometer is usually employed.

The temperature of a body can be determined with precision from a measurement of the radiant energy emitted, because this energy increases at a rate many times as great as the rate at which the temperature increases. The total energy radiated increases at a rate four times that at which the temperature increases, while the spectral energy in the red portion of the spectrum increases at a rate which at 1832°F. is 18 and at 3632°F. is about 10 times the rate at which the absolute temperature increases. (The words "spectral" and "total," when applied to radiant energy, mean respectively the energy of a particular wave length and the sum of the energy of all wave lengths.) Therefore, to attain a precision of 1% in the absolute temperature, the total energy radiated need be measured only to 4%, and the spectral energy radiated need be estimated only to 10 or 20%. With practice one can estimate the brightness of a furnace to about 25% with the unaided eye.

Pyrometers in common use utilizing radiation may be divided into three classes. (1) If the indication of the instrument depends on the heating effect of all or a large part of the spectrum, it is known as a "total radiation pyrometer" or simply a "radiation pyrometer". (2) If the instrument utilizes a part of the spectrum through its effect on a photoelectric cell, it is a "photoelectric pyrometer". (3) If it measures the brightness of an object at some one wave length, it is known as an "optical pyrometer".

Fundamental Principles—The practice of optical, photoelectric, and radiation pyrometry is based upon well established physical laws which may be summarized as follows:

All bodies emit radiant energy whose amount per unit area per unit time depends upon the temperature and surface characteristics of the body. At absolute zero (-273.13°C.) no radiation takes place.

Let $E'_{\lambda\tau}$ be the spectral energy per unit wave length radiated perpendicularly by unit area of a surface at temperature T

Let $A_{\lambda\tau}$ be the ratio of absorbed to incident radiant energy (absorptive power at temperature T for wave length λ)

Let $R_{\lambda\tau}$ be the reflecting power for the same temperature and wave length. Then if the body is opaque so that the incident radiant energy is either absorbed or reflected (none transmitted)

$$A_{\lambda\tau} + R_{\lambda\tau} = 1$$

Now $E'_{\lambda\tau}$, $A_{\lambda\tau}$, and $R_{\lambda\tau}$ will depend on the character of the surface, but in accord-

ance with Kirchhoff's law, for a given value of λ and T , the ratio of $E'\lambda\tau$ to $A\lambda\tau$ is the same for all bodies (in the absence of fluorescence):

$$E'\lambda\tau = A\lambda\tau \times \text{a constant}$$

and since $A\lambda\tau$ cannot exceed unity, it is evident that a body which absorbs 100% of incident radiant energy of wave length λ will radiate the maximum energy of that wave length obtainable from any (nonfluorescent) source at the temperature in question; this energy we will call $E\lambda\tau$. Such a body is called a "black body" because we ordinarily designate the colors of bodies in terms of their appearance by reflected light. At temperatures below those at which it is self luminous, a "black body", as defined above, appears perfectly black. For example, untreated lampblack, which absorbs 95% or more of any incident wave length, radiates about 95% as much energy as a black body. The ratio of the spectral energy radiated by a body to that of the same wave length radiated by a black body at the same temperature is called the "special emissivity", often simply "emissivity", and is evidently equal to $A\lambda\tau$. The corresponding ratio for total radiant energy is called the "total emissivity".

The emissivity, both spectral and total, of lampblack is thus about 0.95 while that of a black body is unity.

The spectral emissivity of most metals in the visible spectrum (excepting that of copper, silver, and gold which is about 0.1) is around 0.3. The oxides of the metals have relatively high emissivities, from 0.5 to nearly 1.

The most perfect black body experimentally obtainable is a small opening in a hollow enclosure the walls of which are at a uniform temperature. The opening need not be particularly small relative to the area of the walls before it cannot be distinguished from a perfect black body by any measurements we can make. For example, the opening in one end of a hollow cylinder closed at the other end has an emissivity above 0.99 when the length is about 5 times the diameter even though the inner walls be of material of emissivity as low as 0.25.

Furnaces, in general, are good black bodies when the temperature inside is uniform. Placed inside such a furnace and allowed to reach equilibrium, all materials appear equally bright and seem to radiate like a black body, since what they emit, $A\lambda E\lambda\tau$, and what they reflect, $(1 - A\lambda) E\lambda\tau$, combine to equal $E\lambda\tau$, the amount that is radiated by a black body. When large errors are met with because of departures of a furnace from black body conditions, they usually arise from lack of uniformity of temperature within the furnace. Suppose a mass of cold material is to be inserted into a hot furnace. Before the mass has been heated any appreciable amount, the radiant energy coming from it will give a false indication of its temperature. If it reflects all or nearly all the light which falls on it, it will appear as bright as the furnace appeared previously, and an optical pyrometer will indicate it to be at the temperature of the furnace. On the other hand if the mass of material has emissivity of nearly 1 it will absorb all the light falling on it and consequently no light will be received from it until it has been heated to the point, about 1100°F., where it itself begins to emit light. This can be summed up by saying that an optical or radiation pyrometer calibrated to read correct when sighted upon a black body will read low when sighted upon an object whose temperature is above that of its immediate surroundings and will read high when sighted upon a body whose temperature is below that of its immediate surroundings.

Optical Pyrometry—The Wien-Planck law is the basis for optical pyrometry and states that $E\lambda\tau$, the energy of wave length λ radiated per unit wave length per unit area by a black body at absolute temperature T is a definite function of λ and T :

$$E\lambda\tau = C_1\lambda^{-5} e^{-\frac{C_2}{\lambda T}}$$

C_1 and C_2 are constants and e is the base of natural logarithms. The law is accurate to 1% for all cases where λ in microns multiplied by T in degrees C. exceeds 3000. Thus for visible light it is accurate within our errors of measurement for all temperatures below about 9000°F.

An optical pyrometer is simply a photometer using a limited range of the visible spectrum (usually red) in which the brightness of the heated body at some one wave length (the "effective wave length" of the instrument) is determined relative to that of a standard source (a black body at the melting point of gold). It usually takes the form of a telescope, which is sighted upon the body whose temperature is to be measured, with means for observing simultaneously the light from a comparison source, and for bringing about a photometric match. The comparison

source must be calibrated in terms of a black body at the freezing point of gold (defined by international agreement as $1063^{\circ}\text{C}.$) either directly or by comparison with another pyrometer which has been previously so calibrated.

In making settings with an optical pyrometer, the photometric match may be brought about either by varying the temperature of the comparison source (the filament of an electric lamp); or by varying the apparent brightness of the hot body or of the comparison source by means of various devices such as absorbing screens. To make the light approximately monochromatic there is in the eyepiece of the telescope a red glass filter which transmits only a narrow band of the visible spectrum. The value of λ to be used in the equation is the "effective" wave length of the light transmitted by the filter glass.

Types of Optical Pyrometer—There are two general classes of optical pyrometers, as follows:

(a) *Variable Intensity Comparison Lamp Type*—This type includes those in which the brightness of the comparison light (an electric lamp) can be varied so as to match the apparent brightness of the light from the body under test, the brightness of the comparison lamp being at all times definitely related to the current which passes through it. This class of instrument is the one which is used in the realization of the International Temperature Scale above the gold point. It requires a precise means of controlling and measuring the filament current, the filament resistance, or the drop of potential through the filament.

(b) *Constant Intensity Comparison Lamp Type*—This type includes those pyrometers in which the comparison lamp filament is maintained at a constant brightness and the brightness of the light from the hot body is cut down to match it by means of an absorbing device such as a glass wedge or a polarizing prism interposed between the hot body and the comparison source. Usually an electric lamp is employed for the comparison source and requires means of standardizing the filament current at only one value, so that the use of a long scale ammeter is unnecessary, resulting in a more compact and lighter instrument. The disadvantages are: (1) That all brightness matches must be made at the relatively low intensity corresponding to the lowest temperature to be measured with the instrument; and (2) the reading involves holding the lamp current at the standard value as well as manipulating the absorbing device.

(a) *Description of Variable Intensity Comparison Lamp Type*—One type of optical pyrometer is shown in Fig. 6. The objective lens, L , is focused so as to form an image of the object, the temperature of which is being measured in the plane

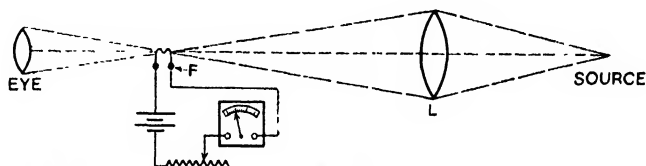


Fig. 6—Disappearing filament, variable current optical pyrometer.

of the filament of a small tungsten filament lamp F . The eyepiece is focused upon the filament and the image, both being simultaneously in focus since they are in the same plane. A red glass filter is mounted in the eyepiece to transmit approximately monochromatic light to the eye. In making an observation, the current through the lamp is adjusted by the rheostat until the tip or some other predetermined part of the filament is of the same apparent brightness as the source viewed. When this condition is reached, the comparison portion of the filament is indistinguishable from the portion of the image of the hot body which it crosses. If the current is too large, it appears as a bright line, and if too small, as a dark line, across the image. The value of the current in the lamp at disappearance of filament is read by means of a milliammeter, and the corresponding temperature is read from a table. In order to avoid deterioration of the filament and blackening of the bulb, the lamp should not be operated at temperatures above $2700^{\circ}\text{F}.$ For higher temperature readings, standardized absorption glasses are placed between the lamp and the objective, so as to diminish the intensity of the light from the object under observation.

A check of an instrument of this type should also include a check of the milliammeter calibration. This is at least as important as that of the lamp.

(b) *Description of Constant Intensity Comparison Lamp Type*—The principle of one of these pyrometers is shown in Fig. 7. It consists of a telescope with an objective lens, A, and an eyepiece, D, an electric lamp, C, and a glass wedge, B. The filament of the lamp is mounted at the focal point of the objective lens and a small section of the filament is viewed through the eyepiece. The observer sees this small section of the filament superimposed on the image of the source sighted upon.

The filament operates at a definite brightness obtained by setting the current through the lamp to a standard value by means of a rheostat and milliammeter. A semicircular wedge of black absorbing glass, which can be rotated through any desired angle, is mounted at B. By varying the angular position of this wedge a

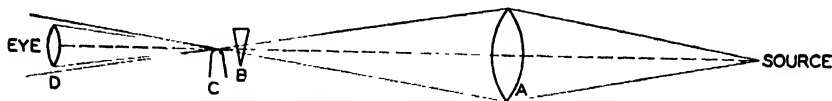


Fig. 7—Disappearing filament, optical wedge type optical pyrometer.

thicker or thinner portion is brought into the line of sight and the brightness of the image of the source viewed may be matched with the brightness of the section of the filament. A scale attached to the wedge is calibrated directly in degrees F. for both high and low range. The high range is secured by interposing a second, fixed, absorbing glass in the line of sight. A red filter glass is used in the eyepiece.

Range and Accuracy of Optical Pyrometer—The useful range of the optical pyrometer begins at about 1200–1500°F., since the radiation emitted by bodies at temperatures less than this is of low luminosity, and balances are difficult even in a darkened room. No upper limit can be set to the temperatures which can be read by means of an optical pyrometer.

The National Bureau of Standards will certify the readings of a commercial type of disappearing filament variable current optical pyrometer to $\pm 9^\circ\text{F.}$ up to 2550°F.; $\pm 18^\circ\text{F.}$ from 2550–3300°F.; and $\pm 36^\circ\text{F.}$ from 3300–5150°F. Readings with the same instrument under practical shop conditions can be repeated by a practiced operator to about one third the limits given above. It does not necessarily follow that all types of optical pyrometers can be operated within the same limits of error.

Precautions for Optical Pyrometer—In adopting the optical pyrometer for a particular use, the limitations imposed by the laws of radiation must be carefully considered. Under some conditions, the radiation emitted from a furnace or from an object within it is so nearly that of a black body that true temperatures are given by a measurement of its brightness. If, however, the temperature of the furnace walls differs considerably from that of an object within the furnace upon which the pyrometer is sighted, or if flames are present, or if bright daylight or artificial light may enter the furnace to be reflected back to the pyrometer, a considerable error may result. One method of reducing stray reflections in a heat treating furnace is to sight into a deep cavity in the metal being heated. Temperatures of closed furnaces can be read by the use of a refractory tube, closed at one end, and so placed that the pyrometer can be sighted through the open end upon the closed end, which is inserted in the furnace. The tube must be thoroughly burned out to remove any tendency to produce smoke before it can be used in making temperature readings.

Care should be taken not to sight through smoke or visible fumes. A considerable depth of clear, nonluminous flame may be sighted through without introducing an important error, but it is safer to turn off the flame while reading, or to sight under it.

When taking temperatures of bodies outside a furnace, black body conditions will not, in general, exist, unless a closed end tube or its equivalent, such as a deep cavity in the body, is used. The radiation from surfaces of carbon and of a few oxides, in the solid condition, such as that of iron, approximate closely to that from a black body so that the optical pyrometer gives temperatures which are accurate for practical purposes on such surfaces in the open. The temperature of steel billets, or sheet, if free from loose scale can be measured successfully in the open with the optical pyrometer.

The emissivity of molten metal surfaces free from oxide is low, and there is a characteristic emissivity for each material, which must be known and the corresponding correction applied to the apparent or brightness temperature to get true temperature. When it is merely desired to repeat conditions on a given material,

and there are no complicating factors such as the changeable film on cast iron (Table II), apparent temperature will serve as well as true temperature and the emissivity correction need not be known. Since liquid metal surfaces are good reflectors, readings should be made from such a position that reflections from flames, lights, or windows do not enter the pyrometer. Table II gives the corrections in °F. to be applied to readings made with an optical pyrometer employing a red filter glass transmitting a mean wave length of 0.65μ .

Table II
Optical Pyrometer Emissivity Corrections
Readings made in red light of wave length 0.653μ .
(To be added to observed temperature)

Observed Temp., °F.	Corrections in °F.					
	Molten Cast Iron ^a	Molten ^b Cast Iron ^c and Steel	Solid Iron ^d	Iron Oxide ^e	Molten Copper ^e	Solid Copper ^f
1400		..	90	1	..	214
1500		..	99	2	..	240
1600		..	112	3	..	267
1700	..	...	122	5	..	294
1800	..	...	133	7	263	..
1900	..	...	148	9	288	...
2000	..	...	162	11	311	..
2100	60	...	175	14	342	..
2200	65	..	..	18	369	..
2300	70	189	..	..	402	..
2400	75	202	..	..	432	..
2500	80	217	..	..	..	...
2600	86	234	..	..	...	...
2700	93	249	..	..	...	...
2800	..	266	..	..	...	...
2900	..	283	..	..	..	...

^aBelow transformation point in surface brightness.

^bWensel and Roeser, Temperature Measurements of Molten Cast Iron, Trans., A.F.A., 1928, v. 36, p. 191. Based on emissivity of 0.40.

^cAbove transformation point in surface brightness.

^dComputed from emissivity value 0.37, Burgess, Bur. of Standards, 1917.

^eBureau of Standards, Tech. Paper 170, 1921.

^fComputed from emissivity value 0.11, Bureau of Standards, Tech. Paper 170, 1921.

A tapping or pouring stream of steel usually shows a set of bright streaks on a darker background. The dark surface is the flat or convex clean metal to which the emissivity of 0.40, on which the corrections in column 3 of Table II are based, is applicable. It is suspected that certain alloying elements, such as manganese, increase the emissivity above 0.40 and consequently lead to high readings of the temperature.

Size of Object—In order to determine the disappearance of the filament sharply it has been found that the image of the hot body as seen in the telescope should be at least four times as wide as the image of the filament. In practice, using generally available instruments, the smallest object that can be sighted on with convenience and certainty must have a dia. of not less than 0.1 in. In principle, however, there is no objection to measuring the temperature of far smaller objects by the comparison of brightness.

If it is desired to measure the temperature of a furnace in which black body conditions are approximated, the pyrometer may be sighted on an opening in the furnace from a position such that it receives direct radiation from the interior of the furnace.

Calibration and Checking of Optical Pyrometer—The optical pyrometer is sent out by the maker with a calibration which should remain good over a period of years if the instrument is carefully used. But changes in calibration may occur, due to deterioration of the lamp filament, clouding of the bulb, pitting or scratching of the objective lens, or changes in the transmission of the absorbing screens if materials other than glass are used. To guard against such changes the instrument should be frequently checked.

At temperatures below 2750°F. checking and calibrating can be accomplished by direct comparison of the optical pyrometer reading with the simultaneous reading of the emf. of a standard thermocouple taken with a potentiometer. If points above this temperature are to be checked, the comparison should be made with the reading of a standard optical pyrometer in the manner described later.

To carry out the former method, the thermocouple is heated in a closed furnace which is free of smoke and incandescent flame, and at such a point in the furnace that the portion of the thermocouple protecting tube immediately surrounding the measuring junction of the thermocouple would be visible through a peep hole if the temperature were nonuniform enough to make it visible. If the work is done in the laboratory, a tubular type electric furnace, not less than 24 in. long and 1.5 in. or less in dia. should be used. The standard thermocouple in this case is inserted at one end of the furnace to such a depth as will bring the end of the thermocouple tube to the middle of the furnace, the other end of the furnace being left open so that the end of the thermocouple tube is in sight.

After bringing the furnace up to the desired temperature, it should be held as nearly constant as possible, and, with the optical pyrometer sighted on the end of the thermocouple tube, readings should be taken on each as nearly simultaneously as possible. Repeat readings until a definite relationship between optical pyrometer and thermocouple readings is established. When, as is usual, a range shifting device is a part of the optical pyrometer, there will, in general, be a considerable overlap between the ranges. In such a case it is well to check at a point lying within the overlap, so that the reading may be applied to each scale, and a check secured upon the accuracy of the range shifting medium.

For checking at points beyond the range of a platinum-platinum-rhodium thermocouple, the same procedure, as outlined above, may be followed, substituting a standard optical pyrometer and a fire clay target for the thermocouple. The fire clay target is mounted in the furnace in place of the thermocouple and the standard and unknown pyrometers alternately sighted into the same end of the furnace.

A more convenient means of checking optical pyrometers up to about 3450°F. is by the use of a ribbon filament tungsten lamp. The filament should be at least $\frac{1}{4}$ in. wide and long enough to ensure a uniform temperature over its central portion. A shallow notch in the filament midway of its length may be used to mark the point on which the pyrometer is to be focused. With a standard optical pyrometer focused on the flat filament the current through the latter is adjusted to produce the desired temperature in the flat filament, as read by the optical pyrometer. The pyrometer to be checked is now substituted for the standard instrument and a reading made with it while the current in the flat filament is held constant. While the tungsten filament is not a black body, if the two optical pyrometers compared are of the same type, employing the same band of the spectrum in each, the readings of both will depart from the true temperature of the filament by the same amount. The standard pyrometer having been originally calibrated to read in terms of black body temperature, the pyrometer being checked will be calibrated in the same terms.

It will be noted that the methods of check just described require the use of an optical pyrometer which is maintained as a standard and used only for checking purposes, and which may be identical in structure with the working pyrometers. Where no pyrometer is available for use as a standard, a reasonably accurate check may be obtained by the use of the flat filament lamp alone, if the current values corresponding to certain fixed temperatures have once been determined, either by the user or by a testing laboratory. The flat filament lamp can then be maintained as a standard source of temperature.

Advantages and Disadvantages of the Optical Pyrometer—Some of the advantages of the optical pyrometer have been brought out in the preceding discussion. These include its utility for measuring high temperatures, and measurements, also at lower temperatures, on inaccessible bodies, moving bodies, small bodies whose temperature would be affected by the attachment of a thermocouple, and for occasional readings when the installation of a thermocouple would not be economical or feasible. Other advantages are that no part of the instrument is exposed to destructive heating effects, and that the indicated temperature is related directly to the temperature of the heated body under test and not to the temperature of some adjacent body (for example a thermocouple), which is assumed to be at the same temperature as the heated body under test.

The principal disadvantages are the ease with which errors may be introduced by absorbing screens of smoke or incandescent gases between the observer and the object under test, and the fact that with most instruments each reading is the result of a photometric match made by an individual observer, and affording an opportunity for dishonest or prejudiced readings, as well as accidental errors.

Errors introduced by uncertainty as to departure from black body conditions have been pointed out in the discussion of the instrument.

Radiation Pyrometers—The Stefan-Boltzmann law states that the total radiation from a black body is proportional to the fourth power of its absolute temperature, or since it is receiving radiation from its surroundings while emitting, its net loss of energy per unit area per unit time is proportional to the difference between the fourth power of its absolute temperature and the fourth power of the temperature of its surroundings. This law is the basis of total radiation pyrometry, and is expressed as follows:

$$E = K (T^4 - T_0^4)$$

where E is the net energy lost by radiation per unit area per unit time; T is the absolute temperature of the black body; T_0 is the absolute temperature of the surroundings; and K is a constant of proportionality.

It is essential in the use of radiation pyrometers to collect the energy emitted from an area of the hot body which subtends a definite solid angle at the instrument, absorb this collected energy in a receiver, and measure the heating effect thus produced in the receiver. The receiver is commonly a blackened disk, on which there is formed an image of the source or of some intermediate opening, and to which are attached the measuring junctions of one or more thermocouples. The cold junctions of these thermocouples are in the same enclosure with the disk, but not exposed to the focused radiation. When radiant energy is received from the source, the disk and its attached thermocouples are heated, their temperature rising until a state of equilibrium is reached, when heat is lost by radiation, conduction, and convection to nearby parts of the instrument at exactly the same rate as it is received by radiation from the source. A temperature differential is thus established between the hot and cold junctions of the thermocouples, the magnitude of the difference being dependent on the rate at which radiant energy is sent out from the source. The rate at which radiant energy is emitted from the source is a function of its temperature. Hence, the emf. developed by the thermocouples in the pyrometer is definitely related to the temperature of the source. The junctions, however, are not heated to the temperature of the source, but to some much lower temperature, usually not exceeding 212°F., even when measuring the temperature of a source heated to 3600°F. or higher. No attempt is made to maintain the cold junctions of the thermocouples at a constant temperature, since the difference of temperature between hot and cold junctions for a given temperature of the source is practically independent of the temperature of the enclosure in which they are placed, over the range of surrounding temperatures to which the instrument may be subjected or about 32-140°F. If the thermocouple materials are so chosen that their emf. is practically constant for a given temperature difference, whether the cold junction is at 32 or at 140°F. or any intermediate temperature, the calibration will be nearly independent of surrounding temperature. This condition is met if the thermocouple materials are chosen from some of the metals commonly employed in thermoelectric pyrometry, such as copper, iron, constantan, Chromel, and Alumel. If one of the materials is an alloy chosen for its high thermal emf. at low temperatures against the other material, without reference to the uniformity of this emf. over the range of surrounding temperature to be encountered, considerable change of calibration with change of surrounding temperature is likely to result.

The sensitive element is the heart of the radiation pyrometer, and many, if not most of the troubles which have been encountered in the practical use of these instruments for temperature measurements may be traced to the thermocouple materials, which have been chosen for their high thermoelectric power, rather than for stability, strength, and freedom from variation with surrounding temperature.

The emf. developed by the thermocouple may be measured by means of a millivoltmeter, or preferably a potentiometer, and the scale of the measuring instrument may be calibrated to read directly in temperature of the source. The scale will not be uniform, since the emf. developed is approximately proportional to the fourth power of the absolute temperature of the source. The measuring instrument may be either an indicator, a recorder, or a controller, or any combination of the three.

Types of Radiation Pyrometers—Commercial radiation pyrometers do not follow the Stefan-Boltzmann law exactly, primarily because not all the wave lengths radiated by the source reach the sensitive element. Part of this energy is generally absorbed by windows, lenses, or mirrors, and not all the radiation reaching the hot junction is absorbed by it, since it is not perfectly black. A secondary reason for

departure from the law is that the emf. response curve of most thermocouples is not a straight line, and the emf. generated is therefore not exactly proportional to the difference in temperature at the hot and cold junctions. Consequently, the term, "total radiation pyrometer", can be used only by courtesy, even in the most favorable case, which is that of an instrument without windows, using a mirror for concentrating the radiation on the thermocouple; hence, the use of the term "radiation pyrometer" is to be preferred, as has been the practice in this article.

Radiation pyrometers may be classed in two ways according to their optical systems: (a) As mirror type or lens type, depending upon the focusing agent; and

(b) as fixed focus or variable focus, depending upon whether means are provided for changing the distance of the thermocouple from the focusing agent to accommodate changes in distance of the object. Classification (a) is the more important. Fig. 8 and 9 represent typical forms of mirror and lens type instruments.

In Fig. 8 the diaphragm opening B and thermocouple b are located at conjugate foci of the spherical mirror DD'. The diaphragm opening acts as a secondary source. Readings are theoretically independent of distance from the source provided that the source is large enough to cover completely the base of a cone determined by the formula:

$$\text{Minimum diameter of source} = \frac{MD}{N}$$

where M = distance from point C to source; N = distance from point C to aperture B; and D = diameter of aperture B. This is a fixed focus instrument.

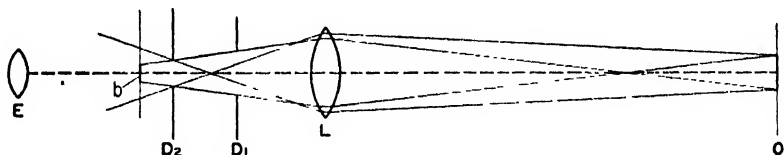


Fig. 9—Variable focus lens type radiation pyrometer.

Fig. 9 shows a typical lens system. The lens L focuses radiant energy from the object O upon the diaphragm D₂ behind which is the thermocouple disk b. D₁ is a limiting diaphragm, which fixes the solid angle of the rays incident on D₂. E is an eyepiece, used in pointing the instrument on the desired portion of the object O. Theoretically the distance between L and b must be changed whenever the distance of the instrument from the object is changed, and it is therefore a variable focus instrument. Practically, beyond a certain distance which is roughly 10 times the focal length of L, the focus is independent of distance, and for such distances it may be treated as a fixed focus instrument. The minimum diameter of the source is fixed by the condition that its image must be at least large enough to fill the aperture D₁.

$$\text{Minimum diameter of source} = \frac{MD}{N}$$

where M = distance from L to source; N = distance from L to D₁; and D = diameter of aperture D₁.

The methods of focusing employed in these two types of instruments have each their advantages and disadvantages. The mirror type instrument can be made to follow the Stefan-Boltzmann law more closely than the lens type, since the selective absorption of the mirror is much less than that of the lens, even when the latter is made of fused quartz, since glass and fused quartz are opaque to much of the long wave length radiation which predominates in the spectrum emitted

by bodies in the usual range of temperature measurements. It can therefore be employed for measuring lower temperatures than the lens type. A further advantage is that the mirror focuses all wave lengths at the same distance, while, due to the dispersion of the lens material, the lens focuses the long wave lengths at a greater distance than the short ones, so that it is impossible to have all parts of the spectrum in sharp focus. In most mirror type instruments the first advantage is sacrificed to a considerable extent by introducing a window between the diaphragm opening B and the thermocouple b (Fig. 8) in order to keep dust, fumes, and moisture from reaching the mirror and the thermocouple, the window being located where it is readily accessible for cleaning.

The lens type instrument has the advantage of not requiring as large a field of view at a given distance. In Fig. 8 it is seen that the mirror type instrument requires a field which covers the base of a cone with its apex at C and limited by the aperture B, while the lens takes in a cone of rays from each point on O, to be focused on D, and if the distance of O from L is such that O need be no larger in diameter than L to form an image filling the aperture in D, a cylindrical surface with the diameter of L extending from L to O will not interfere in any way with the radiation received by D, and b. Hence, the lens type instrument is particularly adapted for use with closed end tubes, of moderate diameter, where the mirror type instrument as shown could not be used. This advantage is obtained at the expense of some loss of sensitivity. It also has the advantage of smaller size, making it adaptable for mounting in positions where space is not available for the mirror type of instrument.

The Stefan-Boltzmann law does not apply to the selected radiation employed by the lens type instrument nor to the mirror type using a protective window. When used to measure the temperature of nonblack bodies, corrections must be applied as in the case of all radiation pyrometers, and in making these corrections it must be borne in mind that these corrections are usually four or five times as large as corrections for optical pyrometers and somewhat smaller than those given for *total* radiation pyrometers. The departure of the correction from the values given for total radiation pyrometers will vary with the material and thickness of the lens or window employed in the particular make of instrument.

Installation—The radiation pyrometer receiving tube should be located where the surrounding temperature does not exceed the maximum allowable value as recommended by the manufacturer. In many cases it is necessary to resort to water or air cooling. Too high a temperature may ruin the sensitive element or damage other parts of the instrument. It is particularly important that limiting diaphragms do not become overheated, as these may radiate to the thermocouple sufficiently to increase the readings considerably.

Proper distance from the source depends upon the size of the source, and upon the type of radiation pyrometer employed. Most manufacturers state the least allowable ratio of source diameter to distance from source. When openings cannot be left in furnace walls, a closed end tube may be inserted with the closed end extending into the region where the temperature is to be measured. The radiation pyrometer is then sighted upon the closed end of the tube. It is important that the tubes used do not give off smoke or such gases as carbon monoxide and carbon dioxide, which absorb radiant heat.

Consideration must also be given to the possibility of mechanical injury to the equipment. If a safe location cannot be found, it is necessary to provide a structure for protecting the tube. Often the water jacket may serve for both cooling and for mechanical protection. In any case the protecting structure must be large enough to provide sufficient cooling area.

Range—Theoretically, radiation pyrometers may be used throughout the entire temperature range. In commercial practice they are available for the measurement of surface temperatures as low as 300°F., and no definite limit can be set to the high end of their range.

Accuracy—Owing to the relatively large source of uniform temperature required, it is more difficult to calibrate a radiation pyrometer than either a thermocouple or an optical pyrometer. Therefore, the accuracy of calibration of the radiation pyrometer, in general, may be expected to be somewhat lower, the amount depending upon the care which has been taken in the calibrating process. In the field, additional errors may enter in various ways, as a result of working conditions differing from those which existed at the time of calibration. Such errors may result from the following causes:

- a. Deviation from black body conditions, the exact corrections for which are unknown, for example, lack of uniformity of temperature within furnaces and interreflection due to irregularity of surface or concave surfaces of bodies in the open.
- b. Parasitic temperature effects at the thermocouple due to nonuniform heating of the housing.
- c. Abnormal radiation from the limiting diaphragm due to overheating.
- d. Dust, stains, or condensed moisture on mirrors, lenses, or windows.
- e. Absorption of radiation by carbon dioxide, carbon monoxide, and water vapor in the line of sight (reduced by use of windows or lenses of glass or fused quartz in the instrument).
- f. Variation of reading with distance from source and with size of source.

It will be evident from a consideration of the above list of possible errors that the accuracy to be expected depends to a great extent upon the nature of the process and the care taken in the installation and maintenance of the equipment. Under favorable conditions, such as a fixed installation reading a constant temperature, an accuracy of 25°F. is obtainable in the range from 1000-3000°F.

Table III gives the corrections in °F. to be applied to readings made with a total radiation pyrometer. These corrections are only approximate and in view of the fact that no existing pyrometer is, strictly speaking, a total radiation pyrometer, they do not apply exactly to any particular instrument. The table serves to point out orders of magnitude of the corrections to be applied. In general, it is preferable

Table III
Total Radiation Pyrometer Emissivity Corrections
(To be added to observed temperature)

Observed Temp., °F.	Corrections in °F.					Platinum ^a
	Iron Oxide ¹	Nickel Oxide ²	Copper Oxide ³	Molten Iron ⁴	Molten Copper ⁵	
1000	60	210	200	...	890	970
1100	65	200	210	...	950	1000
1200	70	190	225	...	1010	1035
1300	70	180	235	...	1070	1070
1400	75	170	250	695	1130	1100
1500	80	160	265	730	...	1135
1600	80	150	275	765	...	1165
1700	85	145	290	800	...	1200
1800	90	135	300	835	...	1235
1900	95	125	315	875	...	...
2000	100	115	...	910	...	...
2100	100	105	...	945	...	...
2200	105	100	...	...	...	...
2300	110	90	...	...	...	...
2400	115	80	...	...	...	...

¹Burgess and Foote, Bureau of Standards Scientific Paper No. 249.

²Burgess and Foote, Bureau of Standards Scientific Paper No. 224.

³Burgess and Foote, Bureau of Standards Scientific Paper No. 121.

⁴Thwing, Phys. Rev. 26, p. 190-192, 1908.

⁵Foote, Bureau of Standards Scientific Paper No. 243.

to determine the corrections to be applied on a given type of work by making simultaneous readings on the surface in question with optical and radiation pyrometers, and determining the true temperature by applying the correction from Table II to the optical pyrometer reading, since the optical pyrometer corrections are much more reliable than those given in Table III for radiation pyrometers.

Photoelectric Pyrometers—Another type of pyrometer, intermediate in character between the optical and the total radiation, is the photoelectric. It does not measure brightness, as does the optical pyrometer, but it takes only a limited portion of the radiant energy from the hot source and converts it by various devices into the energy of an electric current, which can be measured by well known means.

The simplest type of photoelectric pyrometer utilizes the self generative type of photoelectric cell, such as the Photronic cell, in which the radiant energy is converted directly into an electric current by a sensitized surface. These cells are sensitive to the visible spectrum. The current can be sent through a resistance and the emf. drop across the resistance can be measured by a potentiometric indicator or recorder such as those described under "Thermoelectric Pyrometry." Or the current can be amplified, as by an amplifier of potentiometric type, and thus used to operate directly a current recorder.

If the vacuum or gas filled types of photoelectric cell are used, the energy comes mainly from a battery that applies a voltage to the terminals of the cell and thus sets into directed motion the electrons set free by the radiant energy. These cells are influenced by the infra red as well as by the visible spectrum.

A type of photoelectric pyrometer that utilizes the comparison principle with a standard lamp is illustrated in Fig. 10. Two photoelectric cells, P_1 and P_2 , are used to compare the light intensity of the lamp filament F and the heated object O , and an amplifier

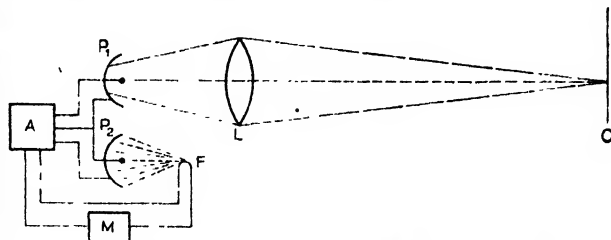


Fig. 10—Comparison type of photoelectric pyrometer.

under control of the photoelectric cells automatically keeps the current through the lamp filament F at the proper value to make the intensity match the illumination from the furnace that reaches P_1 through objective lens L . Temperatures are read from a continuously recording current meter M .

Precautions—The remarks in the paragraph on accuracy will serve to indicate some of the precautions to be observed with all radiation and photoelectric pyrometers. All that has been said under "Precautions" in connection with the optical pyrometer concerning emissivity applies with even greater force here. The difference between the true and the apparent temperature as indicated by a radiation pyrometer calibrated for black body conditions amounts to over 100°F ., when the hot body is of iron, with an oxidized surface, such as a billet, at a temperature of 1700°F .

The size of the object to be sighted on is of much more importance in using the radiation and photoelectric pyrometer than with the optical pyrometer. It is essential that the object shall completely fill the field of view of the sensitive element. The conditions to be satisfied have been discussed under "Types of Radiation Pyrometers."

Calibrating and Checking—In order to carry out a preliminary calibration of a radiation pyrometer a good black body furnace must be available. This may take the form of a graphite tube, electrically heated, and provided with suitably spaced and dimensioned graphite or refractory diaphragms to restrict the loss of heat by radiation to that which enters the pyrometer.

A surface forming a diaphragm across the tube serves as the source on which the pyrometer is focused. The temperature of the source may be determined either by means of a standard platinum-platinum-rhodium thermocouple or an optical pyrometer. A deep closed-end tube of refractory material, of such internal diameter that its closed end completely fills the field of a radiation pyrometer sighted into its open end and heated over a length at least four times its internal diameter, forms a close approach to a black body source. It may be heated in an electric or a gas fired furnace. In this case, the calibration is most conveniently made against an optical pyrometer.

A secondary calibration may be made, in which comparison is made with a similar pyrometer, the calibration of which is known. Comparison is made by exposing the standard and the instrument under test to the same area of the hot body, either alternatively or simultaneously. A source which has been found useful for this type of test is an electrically heated nickel sheet, approximately 6 in. square, and 0.01 in. thick. This is suitable for use up to about 2400°F . In use a tough coating of nickel oxide forms, which does not scale if the cooling from 900°F . to room temperature takes place slowly.

When the radiation pyrometer is used for control purposes only, it may be unnecessary to know the true temperature. Here the optical pyrometer will serve to determine if the radiation pyrometer is retaining its calibration. It is merely necessary to take an occasional reading with the optical pyrometer and note if the radiation pyrometer bears the same relation as before to the observed optical pyrometer reading. Since the radiation pyrometer may give appreciably different results with large sources than small ones, even when the theoretical requirements are fulfilled, and may also show some variation with distance from the source, these quantities should be fixed when possible.

The time lag may vary from the practically instantaneous response of the photoelectric pyrometer, where the speed is limited only by the indicating mechanism and the time of response of the comparison lamp filament to changes of current in it, to a matter of minutes in some types of radiation pyrometer. The more commonly used thermoelectric radiation pyrometers will give a steady reading in from 1-10 seconds after exposure to the source of radiation.

Advantages and Disadvantages—Comparison with the Thermocouple—In the part of its range common to that of the thermocouple, the radiation pyrometer has the following relative advantages:

- a. No contact with the hot body is required, making it possible to measure the temperatures of moving objects, such as billets and strip in the steel mill and rotary kilns in the cement plant.
- b. The time lag is generally much less than that of a thermocouple particularly when the latter must be protected by a heavy ceramic or metal tube.
- c. The instrument is not subject to deterioration through exposure to the high temperature being measured or through contamination by furnace gases.

Disadvantages are:

- a. Relatively large sources are required.
- b. Corrections must be applied to the usual "black body" calibration when black body conditions do not exist in practice.
- c. The accuracy obtainable is generally less.
- d. The first cost is higher.

Comparison with the Optical Pyrometer—Advantages relative to optical pyrometers are:

- a. The personal element does not enter into the measurement.
- b. Direct reading indicators, recorders, and controllers are available.
- c. Lower temperatures can be measured.

The disadvantages are:

- a. Larger sources are necessary.
- b. Corrections for deviations from "black body" conditions are larger and less accurately known.
- c. In general the accuracy is lower.

Lead Baths

By R. B. Schenck*

The various liquid heating mediums employed in the treatment of steel fall into three general classes: Metals, salts, and oils. Of all the metals, lead is the only one which can be considered as a commercial bath material.

Properties of Lead

Melting point, °F.....	621
Heat to raise metal from 60°F. to melting point, B.t.u.....	18
Latent heat of fusion, B.t.u.....	10
Mean specific heat, liquid state.....	0.034
Boiling point, °F.....	2775
Unit weight, solid, lb. per cu.in.....	0.41
Unit weight, liquid, lb. per cu.in.....	0.37

Fig. 1 gives the heat content curve of lead for temperatures between 60 and 1700°F.

Comparative Properties of Lead and Salts

General Comparison—In comparing the properties of lead with those of the commercial salt bath materials, there are certain marked characteristics which differentiate the two classes. Lead is higher in specific gravity, higher in thermal conductivity, lower in specific heat and lower in latent heat of fusion. The melting point of lead is lower than that of any of the salts used for hardening, but higher than most of the tempering salts. Lead has a total working temperature range of about 650-1700°F. The salts, as a class, have a range of approximately 350-2350°F. Lead oxidizes readily, but is otherwise stable, and has no appreciable chemical action on the metals with which it comes in contact. Many of the salts tend to decompose, and some have various chemical effects on the metals. Lead does not adhere to the stock unless impure or oxidized, while the salts cover the work with a film of bath material. Lead is not hygroscopic, whereas the salts all possess this property to a greater or lesser degree. Lead has a much higher heating rate.

Specific Gravity—Steel sinks in all of the salts, but floats on lead unless immersed by suitable fixtures. Lead is higher in first cost on the volume basis, but its lower consumption generally results in lower ultimate cost. The specific gravity of molten lead is approximately 10, while that of the salts is about 2.

Thermal Conductivity—The high thermal conductivity of lead is one of its most valuable properties, tending toward rapid heating, high output, uniform temperature throughout the bath, and high thermal efficiency.

Specific Heat—Because of its low specific heat, the thermal capacity of lead is less than that of most of the salts, even on the basis of volume. This difference, however, is not sufficient to be much of a factor in commercial operation. Low thermal capacity results in greater temperature drops where cold work is introduced and decreases thermal stability. It also tends to reduce time and fuel in bringing a cold pot up to heat; it probably increases thermal efficiency in batch operation, and maintains a greater average temperature differential between the pot and the source of heat.

Latent Heat of Fusion—The low latent heat of fusion of lead tends to cause the formation of heavier layers of solidified bath material when cold stock is placed in the pot. The fact that, independent of melting point and other considerations, these layers actually form more extensively in all salt baths is due to the much lower thermal conductivity of the salts. On the basis of volume, the number of heat units involved is less for lead than for most of the salts, with the result that less time and fuel are required in bringing a cold pot up to temperature.

Melting Point—The melting point of a bath material not only determines the minimum temperature of operation, but also has a pronounced effect upon the heating rate when charging cold stock. The solidified layer of bath material, which forms on cold stock in lead and salt baths, must be completely melted before the temperature of the stock can rise above the melting point of the bath. The lower the melting point, the less will be the weight of frozen material formed. The greater

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the difference between the melting point and the bath temperature, the more rapidly will this layer be removed. Heat conductivity plays an important part in this connection, with the result that, for the same temperature differential, the frozen layer melts much more rapidly in lead than in salt baths. Lead can, therefore, be satisfactorily used at temperatures closer to the melting point, and is less adversely affected in heating rate at higher temperatures. Other things being equal, a bath operating at 1500°F. with a melting point of 700°F. will heat more rapidly than one operating at the same temperature with a melting point of 1300°F. In some cases, where intricate parts would otherwise be inclined to warp or crack in hardening, the retardation of heating due to the solidified layer is distinctly advantageous. Preheating to temperatures below the melting point will decrease the amount of frozen material, and temperatures above the melting point, will, of course, eliminate it completely.

Temperature Range—The wide temperature range of lead, approximately 650-1700°F., makes the lead bath available for the majority of hardening and tempering operations. The lower limit is dependent primarily upon the melting point, while the upper limit is determined by the ability of the pots to stand up and the coverings to give adequate protection against oxidation.

Some of the salt mixtures are used as high as 2350°F. for the hardening of high speed steel, and others are employed for tempering as low as 350°F. All intermediate ranges can be covered by selection of the proper salt mixtures.

Oxidation and Decomposition—Lead is readily oxidized by the air at all temperatures when molten and must be protected by a suitable covering to prevent excessive formation of dross. Lead oxide is sufficiently insoluble in molten lead to preclude any appreciable contamination of the bath as a whole. Aside from this tendency to oxidize, lead is inherently stable in compositions when used as a bath material.

Some of the salts tend to oxidize or decompose on continued use, forming gaseous or infusible products, accompanied by a change in composition of the whole bath. The mixtures containing cyanide oxidize quite rapidly, CN being replaced by CO. Many of the chlorides and carbonate mixtures tend to form sludges which collect in the bottom of the pot and interfere with heat transfer. Additions of cyanides will usually correct this trouble, but cyanide salts are costly and the tendency to form a "case" on the work is sometimes objectionable.

Pitting and Decarburization—Lead baths, under conditions of normal operation, seem to be entirely free from any tendency to pit or decarburize, but many of the salts used in the hardening range are very troublesome in this respect and require special treatment when used on finished parts. Repeated heating and cooling over a wide range of temperature, or desulphurization with cast iron chips, is often necessary to prevent pitting. The frequent addition of "rectifiers," such as sodium cyanide, borax, or boric acid, will eliminate decarburization.

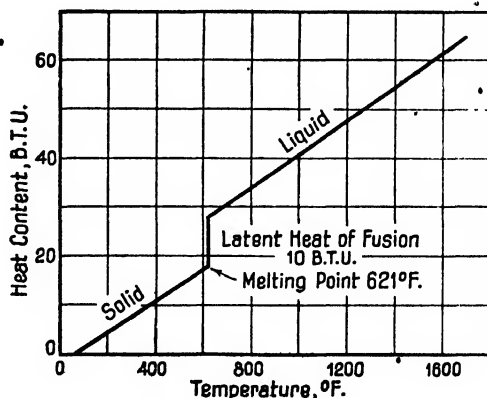


Fig. 1—Heat content for lead

Rusting of the Stock—Lead does not leave any corrosive agent on the stock after heat treatment. Certain salts, especially the chlorides, rust steel very readily in the presence of moisture, so that cleaning with hot water or hot sal soda solution is frequently necessary to remove the last traces of salt.

Chemical Action on Pots—Lead seems to have no appreciable chemical action on the pot materials, but some of the salts are troublesome in this connection. The nitrates and nitrites attack metals violently when slightly overheated and the cyanides are very detrimental to chromium-nickel alloy pots if permitted to enter the combustion chamber. Most of the other commercial salt mixtures have little action on the pots, and the shorter life frequently obtained in comparison with

lead is probably due more to local overheating than to any other cause. Local overheating is much more prevalent with salts, because of their lower heat conductivity. Sludge formation may also be a contributing factor of considerable importance.

Adherence to the Stock—The tendency of lead to oxidize is a troublesome feature, resulting in loss of lead and dirty stock. Suitable coverings must be used, but at low temperatures even the best coverings may be inadequate and special means are often required to clean the work. Above 850°F., however, lead can be well protected and the bad effects of oxidation kept to a minimum. Under proper conditions the steel comes out remarkably clean.

Salts cover the stock with a continuous film of the bath material, resulting in large mechanical losses, but because of the solubility of these materials in water, the work is easily cleaned. The adhering film of salt may be an advantage where it is important to have a fine finish, as this film effectively prevents oxidation by the air upon removal from the bath. The thickness of the film, and, consequently, the mechanical loss, is largely dependent upon the fluidity of the bath.

Affinity for Water—The fact that lead does not absorb water is a decided advantage. Some of the salts are objectionable in this respect, and require careful handling in order to avoid dangerous explosions when they are added to a molten bath. All the salt bath materials have more or less affinity for water and should be shipped and stored in air-tight containers.

Heating Rate—The heating rate, or time required to bring a piece of steel of a given size up to the temperature of the bath, is mainly dependent upon heat conductivity and melting point. Lead so greatly excels in heat conductivity that, for any temperature within its range of operation, very few of the other bath materials approach it in rate of heating.

Fig. 2 shows the comparative heating rates of steel in a lead bath, a cyanide bath and an oven furnace. The test piece consisted of a cylinder of low carbon steel with a stem on one end bored to admit a thermocouple. All of the units tested were of sufficient size to prevent more than slight temperature drops when the cold test piece was introduced. The lead and cyanide baths were of exactly the same size. The baths and furnace were stationary in temperature and remained practically so without firing, throughout the duration of the test. The cyanide mixture showed by analysis, at the time the test was performed, a composition of approximately 14% NaCN, 14% NaCl, and 72% Na₂CO₃. The extremely rapid rate obtained in lead is clearly shown. It is also interesting to note that lead heats to the required

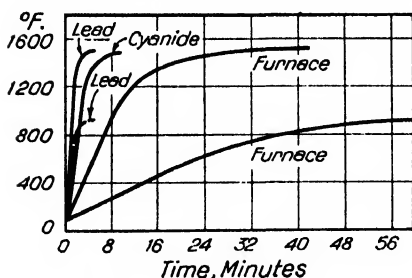


Fig. 2—Comparative heating rates of steel in a lead bath, a cyanide bath, and an oven furnace.

temperature in the same time at 900 and 1500°F., while the oven furnace takes longer to heat to the lower temperature.

Quality of Lead Used—The grade of lead purchased for baths is not of great importance. Ordinary pig lead seems to answer every requirement. Special grades, claimed to be superior for lead pot work and marketed at a higher price, apparently give no better results than the regular commercial pig. Tin, even in small percentages, tends to cause lead to stick to the work and is to be avoided. Tin contamination is sometimes encountered in lead which has been refined from

cross. Sulphur is also claimed to be an objectionable impurity.

Pot Materials—There are, in general, three classes of pot materials: Cast iron, steel, and the special alloys.

Cast Iron—Cast iron pots, if properly made, usually give good service at temperatures below 1300°F. At higher temperatures, cast iron has not been found satisfactory, except in small units operated at low output. Its composition ranges from ordinary gray iron to the so-called alloy iron, made with additions of steel scrap and containing small quantities of alloying elements.

Steel (Cast and Pressed)—Cast steel is used for all temperatures throughout the range of lead. Below 1300°F. it gives excellent results. At higher temperatures its life depends largely on the conditions of service. The chemical composi-

tion varies considerably, and within certain limits is of much less importance than freedom from porosity. Many different compositions give equally good service if the castings are sound.

Pressed steel pots are also successfully used throughout the temperature range of lead. Their advantage lies in light weight and freedom from porosity. Unfortunately they do not possess the flexibility of design attainable with cast steel, and on account of die cost are, for the most part confined to standardized shapes and sizes.

Special Alloys—Most of the special alloys come under three general classifications: High nickel-chromium, low nickel-chromium, and chromium. The alloys of the first class contain in percentage about 65 Ni and 15 Cr; the second class 35 Ni and 15 Cr; and the third class 25 Cr. These materials are all much higher in price than steel, and to prove economical must give correspondingly longer service. They are always used at temperatures over 1300°F., as they cannot compete with cast iron and steel in the tempering range.

Special alloy pots are usually cast, although certain compositions are obtainable in pressed form. As in the case of cast steel, the composition of a cast alloy pot is often of less importance than its freedom from porosity. The advantages and the limitations of design of the pressed steel pot apply in even a greater degree to the pressed alloy pot.

Pot Design—An important factor in obtaining efficient service is the design of the pots. Sharp corners and abrupt changes of section should be avoided wherever possible. Large radii in corners below the lead level are especially important.

Thickness of section is a much disputed point. The cast special alloys, as a rule, do not require as heavy bottoms and sidewalls as cast steel. Extremely thin sections tend to cause failure due to bulging followed by cracking, while thick sections often fail to give service in proportion to their greater cost, especially when operated at high temperatures and high output. In other words, the life of a pot is not directly proportional to its thickness, except possibly within narrow limits. The premature failure of thick pots is probably often due to the greater temperature difference between the inner and outer surfaces. Pressed pots of either steel or special alloy are necessarily of quite uniform section throughout.

Furnace Design—Lead baths are generally fuel fired with either oil or gas. Electrically heated units, in which the heat is applied by means of resistors surrounding the pot, are also in use. The principal advantages of electric heat consist of exceptionally long pot life and cleanliness. It is especially well adapted for use in the machine shop. The following discussion, however, is confined to fuel fired baths.

The design of the furnace and especially of the refractory setting, which supports the pot and forms the combustion chamber, should receive the most careful consideration. Proper location of burners and vents, adequate combustion space, correct vent area, length of flame travel, location of splash brick, and height of combustion chamber are all items which, if neglected, may result in unsatisfactory and costly operation.

Lead Bath Coverings—(Solid Coverings)—As previously stated, lead is readily oxidized by the air at all temperatures when molten, and must be covered with some suitable material, in order to avoid excessive lead loss and dirty stock. Wood charcoal, corncob charcoal, charred nut shells, charred leather, coal coke, and petroleum coke are some of the materials in commercial use as pot coverings. Hardwood charcoal, size No. 3, such as is used in the manufacture of carburizing compounds, is one of the best coverings, but is not always the most economical. In determining the most suitable covering, a great deal depends on the nature of the work and the temperature of the operation. In hardening transmission gears, the best covering obtainable is generally none too good, while in hardening axle shafts which are to be later drawn in lead, coal coke, or the cheapest grade of charcoal screenings, will answer the purpose.

The action of the carbonaceous coverings is both chemical and mechanical. Their efficiency depends, to a great extent, upon the rapidity with which they burn, and the temperature at which burning starts, sometimes called the "kindling temperature." The chemical action is due to the reducing effect of CO gas, which is

generated by the combustion of the covering. Below the kindling temperature, no CO is formed and the protective effect becomes entirely mechanical. Coal coke has such a high kindling temperature that it is practically useless in the tempering range, although it makes an excellent covering for some classes of work at the higher temperatures. Wood charcoal has a much lower kindling temperature, somewhere in the neighborhood of 850°F., and will protect the lead much less effectively at 800 than at 900°F., in spite of the fact that the tendency of lead to oxidize increases rapidly with temperature. The size of the covering must also be considered and depends largely on the nature of the job. Sizes much larger than No. 3 charcoal are generally unsatisfactory.

Depending on the nature of the work, the kind of covering employed, and the temperature of the operation, the bath must be skimmed more or less frequently. The coverings burn to an ash, which collects rapidly and interferes with the action of the CO gas. Moreover, the protective effect is never perfect and a certain amount of oxide will always form, even under the best conditions. This ash and oxide must be removed and replaced with new material every so often or trouble will result.

Prevention of Lead Adherence—In order to more effectively prevent adherence of lead, the stock is sometimes coated with a thin film of salt or some other material, before being placed in the pot. The salt is applied by dipping the parts in a hot saturated brine solution, which dries quickly and leaves a light deposit of NaCl. This method has been used extensively on parts which are difficult to keep clean, and is applicable at all temperatures below 1475°F., the melting point of NaCl. Numerous other washes, such as calcimine and emulsions of lampblack in kerosene, have been used for the same purpose.

At low temperatures, below the kindling point of the covering, the question of cleaning the stock often becomes a serious problem. This difficulty has been overcome by dipping the stock in molten caustic soda immediately following its removal from the lead and then quenching in water. The result is perfectly clean work and a large saving in lead. The caustic soda pot is held at a temperature slightly below that of the lead. Sodium nitrate has been successfully used for the same purpose.

Liquid Coverings—Molten salts of suitable composition make effective coverings, but are generally more expensive than solid coverings. Cyanide mixtures are very efficient, but their cost for large production is prohibitive. Mixtures of NaCl, Na₂CO₃, and K₂CO₃ have been used successfully on small units. Salt coverings have the advantage of producing exceptionally clean work and keeping the lead loss to an extremely low figure. The salt consumption, however, is usually a source of considerable expense. Many salts, other than those mentioned above, have been tried without success. Caustic soda, which might be thought suitable for low temperatures, causes a gradual oxidation of the lead, while sodium nitrate is still worse in this respect. Most of the mixtures of chlorides and carbonates tend to decompose and form infusible products which are very objectionable.

A decided objection to the use of salt covering on large pots is the great amount of heat radiated from the surface of the bath, which results in bad working conditions for the operators and lowers thermal efficiency. The solid coverings have a marked blanketing effect, which is almost entirely absent with the salts.

Pot Failures—With properly designed and operated units, pot failures are due to three general causes: Porosity, cracking and oxidation. Cast iron almost always fails by cracking. Cast steel usually fails from porosity, and from oxidation, as a secondary effect, when blow holes open up as the metal scales away. Failures with cast steel pots are seldom due to cracks. Cast alloy pots usually fail from cracking, and in many cases from porosity. They suffer very little from the effects of oxidation, except where metal segregation occurs. Pressed steel pots nearly always fail from oxidation, and pressed alloy pots usually from oxidation or cracking.

Lead Poisoning—There have been many erroneous statements made in regard to lead poisoning. According to some of the older authorities, the very atmosphere in the neighborhood of a lead bath was supposed to reek with noxious and poisonous vapors, which would inevitably result in the death and destruction of all who lingered in the vicinity. Such statements to the contrary, lead poisoning is very seldom encountered in any modern shop. Two simple precautions are necessary: Keep the waste gases from the combustion chamber out of the shop by employing suitable

hoods and stacks, and keep finely divided lead oxide out of the atmosphere. Operators have suffered from lead poisoning by continually breathing the products of combustion, which often carry lead compounds because of accumulations of lead under the pot. Poisoning has also resulted from lead oxide in the form of dust, which was continually thrown into the air during a hammer straightening operation on shafts. Removal of this oxide by quenching the shafts from the tempering bath eliminated the trouble. The surface of a lead bath does not give off any injurious vapor at temperatures of commercial operation.

Caution—Material to be immersed in a lead or salt bath with any degree of safety must be entirely free from moisture. When moist material is immersed in a molten bath, the moisture is instantly changed into steam, thus causing a violent eruption of the bath, which may burn the operator severely.

Methods of Operation—Lead pot furnaces may be operated by either the batch or continuous methods. For tempering, the former is the more satisfactory, while for hardening, both methods are successfully employed. In using the batch method, the pot is filled to its full capacity and the work completely removed as soon as the desired temperature is reached. It is generally necessary to shut off the burner before removing the work, but in some hardening operations, if charging and discharging are sufficiently rapid, the burner can be allowed to remain open. With the continuous method, the bath is held at the desired temperature, part of the load being removed and replaced with cold work at stated intervals. Automatic handling of the stock has been applied to lead baths with a certain degree of success but many difficulties have been encountered which are not met with in oven furnaces. Parts requiring local heating are often quite readily handled with rotary fixtures in round pots, or with chain conveyers in long rectangular pots.

Applications—While the lead bath still has a definite field of utility, it has been largely replaced in the treatment of many parts by the more economical automatic oven furnace, which has been so highly perfected in recent years.

The lead pot is extensively used for local hardening and tempering. Many jobs requiring local heating cannot be satisfactorily handled in any other way. By proper manipulation, it is possible to so treat a bar of steel that it will have a number of alternate hard and soft sections between the two ends. Heating can be much more effectively localized in lead than in any of the salt mixtures. For parts which must be free from scale, the lead bath is extremely useful. In tool hardening, the lead bath has many applications. It is used for hardening broaches, reamers, drills, and numerous other tools. It makes an excellent quenching medium for high speed steel, as originally developed in the "Taylor White" process.

Salt Baths*

General—By the term "salt bath" is meant a bath, composed of one or more salts, which is designed to form a heating medium inert to the work, and which is intended to impart neither a hard nor a soft surface to metal, but to produce work having the same chemical composition from surface to interior as it had before heating.

The value and economy of a salt bath depend upon its application to suitable jobs and upon its use within the limits of temperature at which the salt mixture operates at highest efficiency.

Salt Bath vs. Oven Furnace—(1) The bath tends to heat work more uniformly than do most ovens. The work is ordinarily suspended in a bath, but is usually laid on the hearth in an oven; and the nature of a bath naturally eliminates contact of cold air with the work, whereas many oven furnaces are not air tight. If an oven furnace is air tight, and if the work is suspended therein or otherwise arranged so that heat absorption is equal on all surfaces, there is no reason why the heating will not be at least as uniform as in a salt bath.

(2) Salt baths, if properly maintained and operated, eliminate scaling. This is an advantage of salt baths over air furnaces. Controlled atmosphere furnaces may, however, equal salt baths in this respect. Salt adhering to work removed from a bath also helps to prevent scaling while cooling or during transfer to the quenching medium, although a salt which does not dissolve quickly in the quenching medium may hinder quenching.

(3) Salt baths, as here considered, do not carburize, but in general tend to decarburize steel, the activity of a bath depending upon the temperature at which it is operated. It is possible to obtain salt baths which, if used properly decarburize so slightly that the soft skin cannot be detected after quenching. Air furnaces may be carburizing, decarburizing, or acceptably neutral, depending on the atmosphere within the furnace.

(4) Salts heat the work more rapidly than do air furnaces. This may be either an advantage or a disadvantage, depending on the application and on the design of the parts. The rapid heating, together with the proximity of the heating medium and the atmosphere, makes salts usually more desirable for local heating.

(5) The salts themselves and the pots containing them are items of expense not encountered in oven furnace operation.

(6) Salts carried over with work to a quenching bath may change the composition of the quenching medium. This does not occur with mineral oil, but may with water or any liquid in which the salts in question are soluble.

(7) Work must be dry and preferably slightly preheated, before immersing in a salt bath.

(8) Salts flux with many refractories at high temperatures. This means that furnace maintenance may be more costly if salt baths are used.

(9) The question of warping and cracking of work heat treated in a salt bath is one to which no general answer can be given. In some cases, where the work is preheated and, due to its nature, may be heated more uniformly in a salt bath, warping and cracking may be less with a bath than with an oven. On the other hand, where slower heating is desirable, a well designed oven furnace may give better results.

Salt vs. Lead Baths—(1) Because of the solubility of salt in water, it is usually more easily cleaned out of holes and depressions in work than lead.

(2) Lead may be melted and heated more rapidly than can salt baths, owing to the higher conductivity of the former.

(3) Work floats on lead, and usually must be held firmly in place, whereas metals need merely be suspended in salt baths.

(4) Most salts are to some extent hygroscopic, and must be stored in air tight containers when not in use.

(5) Aside from its tendency to oxidize, lead maintains a stable composition, whereas most salts undergo some decomposition during use. When a salt bath is used for hot quenching, the high temperature of the quenched work may decompose some of the bath constituents, such as nitrite, which must be periodically replaced to maintain the desired composition.

(6) Lead is neutral to most refractories, though lead oxide is not.

*Prepared by the Subcommittee on Salt Baths. The membership was as follows: W. P. Eddy, chairman; E. F. Davis, W. J. Harris, H. D. Ford, and J. H. McCadle.

(7) Lead costs more initially than most salts.

(8) Less mechanical (drag out) loss is suffered by a properly protected lead bath than by salt baths during operation. On the other hand, the salt adhering to work may be classed as a protective coating. Salt is more easily removed than lead due to its solubility in water.

(9) The surface of a lead bath must be protected from the atmosphere.

(10) Lead heats work more rapidly than do salt baths; hence lead is usually preferable for local heating.

General Characteristics of Salt Baths—The ideal salt bath should be inert to the metal heated in it; should not change in composition or form a sludge; should not fume corrosively; should clean easily; should not pit or corrode either the work or the bath container; should be thinly fluid at the operating temperature; should be nonhygroscopic; should not promote rusting of work subsequent to heat treatment; and should be low in cost.

The perfect salt bath, however, has not yet been discovered. Practically all the salts used for heat treating are hygroscopic to some extent. All adhere to the work when it is removed; the amount of drag out varies, of course, with the viscosity of the bath and with the shape of the work, but is usually between 4 and 24 oz. of salt per hundred lb. of work. There is always a corrosive action at the surface of a salt bath, affecting containers, thermocouple tubes, hooks, and partly immersed work; this action is more severe the higher the temperature.

Classification of Salt Mixtures—For convenience in the consideration of specific salt mixtures, we may divide them into three groups. Low temperature salts are used for tempering, and for quenching carbon or low alloy steels. Medium temperature salts are used for heating the same steels for hardening, normalizing or annealing, and for quenching high speed steels. High temperature salts are used for heating high speed and certain other high alloy steels for hardening.

Low Temperature Baths—Low temperature salt baths are composed of nitrates and nitrites of the alkali metals. Sodium nitrate, sodium nitrite and potassium nitrate are the salts most commonly used. Sodium nitrate, melting at 586°F., may be used at temperatures above 650°F. The eutectic mixture of potassium nitrate (56%) and sodium nitrite (44%) melts at 295°F. and may be used at 325°F. or above. A mixture of potassium nitrate (51.3%) and sodium nitrate (48.7%) melts at 425°F. and is suitable for use above approximately 475°F.

The maximum temperature recommended for any of these low temperature baths is 1100°F., as at higher temperatures they attack the work and the bath containers. Local overheating of the bath container must not be permitted, else failure will occur. Nitrates and cyanides react together violently, when hot, and the two should be kept apart; serious explosions have occurred as a result of failure to observe this precaution.

These mixtures are commonly used for tempering all types of steel. The potassium nitrate and sodium nitrite mixture given above is the most desirable for general purpose work, as it has the widest temperature range of usefulness. However, if the low temperatures are not to be used, one of the other mixtures will be cheaper. Work should be thoroughly cleaned of oil, salt from brine, scale, or soot, before immersion in any of these tempering baths. Otherwise, contamination of the bath will occur, resulting in thickening, sludge formation, increased drag out, lowered efficiency, and difficult cleaning after tempering. Any of these mixtures, if uncontaminated, will dissolve easily in water, and work may be easily cleaned by simple washing. If desired, work may be cooled in oil after tempering, and can then be cleaned quickly in an alkaline solution.

In addition to the above mentioned use, these baths may be used, either alone or with additions to other salts, for blueing and blacking steel. To obtain a black, it is necessary to heat to 900-1000°F. Considerable skill and experience may be required to produce uniform blue or true black colors.

Another increasing use of nitrate baths is in the heat treatment of the strong aluminum alloys. The solution treatment is performed by quenching from temperatures, varying with the alloy, between 900 and 1000°F. Precipitation treatment consists of heating for considerable periods at 300-400°F. Large sizes (% in. and over) of duralumin rivets may be heated in these baths for hot riveting. Unless the salt is completely removed afterward, however, it may accelerate corrosion.

These baths may be used for quenching carbon and low alloy steels. The bath may be maintained at any temperature between 300 and 1000°F., depending upon the hardness and physical properties required in the quenched work. Some decom-

position of the bath constituents may occur due to the local action of the hot work being quenched, and some pitting of the work may occur. The intensity of these actions depends on the size of the work and its temperature before quenching.

Medium Temperature Baths—Salt baths in the medium temperature class are used for heating carbon and many alloy steels for normalizing, annealing, and hardening; for quenching and tempering high speed steels; and for heating brass, bronze, nickel silver, copper, gold, and other nonferrous metals and alloys for bright annealing treatments.

Salt mixtures for use in the medium temperature range are perhaps more varied in composition than are the low temperature mixtures; but, in general, the mixtures are eutectics and are composed of chlorides, or of chlorides and carbonates.

The chloride carbonate mixtures (such as 50% potassium chloride and 50% sodium carbonate, which melts at 1085°F.) are satisfactory for heat treatment of nonferrous metals. Carbonates in a salt bath tend to decarburize steel. Such mixtures are sometimes used for heating steel, however, with additions of sodium cyanide to prevent formation of soft skin on steel parts. The action of the cyanide is to replace some of the carbon lost during heating with nitrogen. The desirability of this practice is often questionable, especially with steels of over 0.75% carbon. Addition of cyanide to a bath may, however, improve ease of cleaning of work.

Baths consisting of chlorides only are generally preferred for heating steel. The lowest melting chloride mixtures contain calcium chloride (for example calcium chloride 67% and sodium chloride 33%; melting point 940°F.). Calcium chloride, however, because of its deliquescence and its tendency to corrode work, is in general not a desirable constituent. The alkali chloride mixtures (for example, potassium chloride 56% and sodium chloride 44%; melting point 1220°F.) are the most easily handled.

However, even the chloride mixtures, though originally inert to steel, gradually oxidize, when molten, to oxychlorides, then oxides or carbonates. As a result, these mixtures, also, may decarburize steel after some use. Additions at regular intervals of $\frac{1}{4}$ – $\frac{1}{2}$ % of the weight of the bath of a suitable "rectifier" will usually counteract the tendency of the bath to decarburize. The rectifier (boric acid, fused borax, or boric oxide) converts oxides and carbonates in the bath to stable metaborates, which usually form a sludge that can be removed and discarded. Such rectifiers are of no value when added to a chloride-carbonate bath; they may advantageously be used only in chloride mixtures.

The medium temperature bath mixtures can be used from approximately 100°F. above their melting points up to about 1650°F.

High Temperature Baths—The high temperature baths are generally used in the temperature range of 1800–2400°F., primarily for hardening high speed steels. The salts used in these bath mixtures are barium chloride, borax, sodium fluoride, silicates, and occasionally magnesia or lime. Rectifiers containing ferrosilicon have also been used. These baths are not eutectic mixtures, but are glasses; they have no sharply defined melting point, but soften gradually when heated. The melting range is usually between 1600 and 1900°F.

Some of these baths, when new, are not inert to steel, but become satisfactorily so after some use, so that high speed steels can be heated without occurrence of scaling or decarburization. In some cases, trouble may be experienced with edges of fine tools dissolving or "washing away."

For preheating, the same salt is sometimes used, maintained in or just above its melting range; the work should be held in the preheat bath until the salt runs off freely when the work is lifted from the bath. In order to shorten the time in the preheat bath, an additional semimuffle or muffle heating should be used, in which the work is heated to 1000–1200°F. before transferring to the salt preheat. A single preheat of the muffle or semimuffle type, as in air furnace practice, may be substituted for the double preheat, but scaling of work usually makes this undesirable. Modern practice usually involves the use of a chloride or other salt mixture of lower melting range for the preheat bath.

Perhaps the greatest disadvantage of the high temperature bath mixtures is that none of them are easily cleaned from the work. It is almost imperative that a salt quench be used. The salt quench consists of an added unit in the system in the form of a pot containing a chloride-carbonate bath, with or without cyanide, maintained just above its melting point, and preferably below 1200°F. Such a bath reacts chemically, with some sputtering, with the high temperature salt adhering to the work as it is lowered into the quench, the reaction being between the carbonates or cyanides in the quenching bath and the high temperature salt. The prod-

ucts of the reaction form a heavy sludge in the quench pot. This sludge must be frequently removed and thrown away. The action of the quenching salt has an important bearing on the quality of work. While a quenching mixture containing a large proportion of carbonate is desirable from the cleaning standpoint, a large excess of carbonate may cause formation of soft skin on the work, through the decarburizing action previously noted. Quenching in a chloride mixture or in oil or air gives greatest freedom from soft skin, but work quenched in any of these media is extremely difficult to clean. Immersion in vigorously boiling 10% sodium cyanide solution for $\frac{1}{2}$ hour or more, followed by wire brushing, is often used to clean work. Dipping the work in molten caustic soda at 1050°F., after tempering, is usually helpful.

Salt Bath Operation—The most important general rule of salt bath operation is: Do not allow the bath to become contaminated with anything. This applies to salt baths in all temperature ranges.

Pure salts should be used in all mixtures. Sulphates are particularly undesirable in all mixtures, and nitrates should not be present in medium or high temperature baths. To eliminate small amounts of these corrosive impurities from a bath, add about 5% of the weight of the bath of clean, dry cast iron chips, preferably while the bath is near the top limit of its temperature range, stir well, allow to settle and remove the sludge formed. Ferrosilicon may be used for this purpose in high temperature baths. If a rectifier is to be used, it will serve also to eliminate sulphates and nitrates. The best baths are usually made by specialists in salt bath manufacture.

Heat salts slowly while solid; they are all poor conductors of heat, and the rate of heat absorption is therefore limited when there can be no circulation. An attempt to melt too quickly only results in overheating of the pot with consequent short life, and possible overheating of the salt adjacent to the pot.

When additions of salt are to be made, it is safest to place the required quantity on top of the solid salt before melting. If this is not practicable, because of 24 hour operation or high drag out which necessitates more frequent additions, be sure the added salt is dry.

A salt having low melting point is desirable when large work is to be heated, as the immersion of a large mass of metal lowers the temperature so much of the adjacent salt that a thick coating of solid salt will form on the work. If possible, large work should be preheated up to the melting point of the bath, then immersed with the bath just above its melting point, and the bath and metal slowly heated to the desired temperature.

Melting point of the bath is not usually important for small work, provided the melting point is not too near the operating temperature. Small pieces can be immersed, preferably after some preheating, with the bath at the operating temperature. If many pieces are to be heated at the same temperature, it is advisable to establish a semicontinuous procedure, immersing a small quantity immediately after removing an equal quantity.

It is advisable to remove the thermocouples, at the end of a run, before the salt freezes.

Salt baths weigh from 100 to 150 lb. per cu. ft., molten.

Salt Bath Furnaces—Oil fired pot furnaces are satisfactory in large sizes, though not, as a rule, so desirable as other types in smaller units, because of the long flames which are characteristic of oil burners. Gas firing is usually satisfactory, provided furnaces are properly designed.

Electric pot furnaces of several types have been more or less successfully used. A resistance furnace, with metallic heating elements surrounding the pot, may be used for low and medium temperature operation, provided care is taken to keep salt away from the resistors.

The direct resistance type of furnace has been used with some success. Two or more electrodes are lowered into the bath, or the pot can serve as one of the electrodes. The salt is heated by the current passing through the bath itself. Special means must be taken in this furnace to start the melting of the solid salt, and care must be taken during melting to prevent local overheating of the salt. After the bath is entirely molten, however, this type of furnace is inherently very efficient, as the heat is generated where it is wanted.

A few generally important points of design and operation, which apply more or less to all types of bath furnaces, follow:

1. Apply heat as near the top of the pot as possible, in order to obtain more uniform temperature and to start melting solid salt at the top. All molten

salt baths are hotter near the bottom than at the top, because of the high radiation losses from the surface. As all salt bath materials expand when heated, melting first near the bottom causes heavy pressure to be applied to the pot, with resultant deformation and early failure.

2. In fuel fired furnaces, the flame should not impinge upon the pot. Cylindrical pots, with tangentially placed burners near the top, should be used whenever possible. The furnace should be vented at the bottom for the removal of flue gases. It sometimes pays to conduct the waste gases into an adjacent chamber where they may be used for preheating work.
3. Bath materials and the fumes therefrom should be kept out of combustion or heating chambers, as refractories and heating elements are readily attacked by salts.
4. Combustion chamber atmosphere is important in relation to pot life. With steel pots in fuel fired furnaces, a slightly reducing or soft flame is desirable. All openings should be plugged when the furnace is shut down, to prevent circulation of air which would scale the hot container.
5. Furnaces should be of sufficient capacity to prevent a large drop in bath temperature when work is immersed, and to allow all work to be immersed without touching or nearly touching the sides or bottom of the pot.
6. To conserve heat, pots should be covered whenever possible.
7. If work is to be totally immersed in a salt bath, wire mesh baskets may be used for small parts, and larger work may be suspended on a hook by means of soft iron wire. The wire should be well annealed and must be twisted lightly with pliers in order to insure against work being lost in the pot when the wires become hot and sag.
8. A spare pot should be kept near every bath furnace. A small leak in a fuel fired furnace will quickly be detected, as white "smoke" will come out of the flue gas exhaust vent. Time will then usually be available for the molten bath material to be ladled into the new pot, after which the failed pot can be easily removed and the newly filled pot let down into the furnace, with little loss of time.

Temperature Measurement—Mercury thermometers made of metal may be used in low temperature tempering baths. These instruments are cheap and sufficiently

Melting Points of Salts

Salt	Melting Point, °F.	Salt	Melting Point, °F.
Barium chloride	1784	Potassium hydroxide	716
Barium fluoride	2336	Potassium nitrate	631
Boric oxide (anhydride)	1071	Potassium nitrite	567
Calcium chloride	1422	Sodium carbonate	1564
Calcium fluoride	2480	Sodium chloride	1479
Calcium oxide	4862	Sodium cyanide	1047
Lithium chloride	1136	Sodium fluoride	1796
Lithium nitrate	491	Sodium hydroxide	605
Magnesium fluoride	2545	Sodium metaborate	1771
Magnesium oxide	5072	Sodium nitrate	586
Potassium carbonate	1636	Sodium nitrite	520
Potassium chloride	1429	Sodium tetraborate	1366
Potassium cyanide	1174	Strontium chloride	1603
Potassium fluoride	1616		

Melting Points of Salt Mixtures

All mixtures are eutectics except those marked.* Proportions given are percentage by weight.

Mixture	Melting Point, °F.
Lithium nitrate 23.3, potassium nitrate 60.4, sodium nitrate 16.3	250
Potassium nitrate 53, sodium nitrate 7, sodium nitrite 40	285
Potassium nitrate 56, sodium nitrite 44	295
*Potassium nitrate 51.3, sodium nitrate 48.7	426
*Sodium nitrate 50, sodium nitrite 50	430
Lithium chloride 45, potassium chloride 55	666
Barium chloride 31, calcium chloride 48, sodium chloride 21	806
Calcium chloride 66.5, potassium chloride 5.2, sodium chloride 28.3	939
Calcium chloride 67, sodium chloride 33	941
Barium chloride 48.1, potassium chloride 30.7, sodium chloride 21.2	1026
Sodium chloride 27, strontium chloride 73	1049
*Potassium chloride 50, sodium carbonate 50	1085
Barium chloride 35.7, calcium chloride 50.7, strontium chloride 13.6	1110
Barium chloride 50.3, calcium chloride 49.7	1112
Potassium chloride 61, potassium fluoride 39	1121
Sodium carbonate 56.3, sodium chloride 43.7	1177
Calcium chloride 81, potassium chloride 19	1184
Barium chloride 70.3, sodium chloride 29.7	1209
*Potassium chloride 56, sodium fluoride 44	1220
Sodium chloride 72.6, sodium fluoride 27.4	1247
Barium fluoride 70, calcium fluoride 15, magnesium fluoride 15	1454
Barium chloride 83, barium fluoride 17	1551
Calcium fluoride 48, magnesium fluoride 52	1738

accurate and durable at the low temperatures involved, though they do not permit the use of automatic control. For higher temperatures, thermoelectric pyrometers are universally used.

The protection of thermocouples is important in bath heat treating. The wires must be protected by a metal tube which is not rapidly decomposed by the bath, to prevent contact of the bath material and the couple. Such contact not only results in shortened thermocouple life, but also immediately causes false readings. The hot junction of the thermocouple should always be immersed in the bath to the same depth as is the middle of the work, and should be placed close to the work and as far from the side of the pot as possible.

Quenching Equipment*

Fundamentals of the Quenching Operation—The type of equipment used for quenching depends first upon whether the quenching medium to be employed is a solid, a liquid, or a gas.

In designing or selecting equipment for quenching in liquids such as oil, water, and aqueous solutions, the fundamentals of the quenching operation must first be taken into consideration.

The objective of quenching is to cool the steel at the desired rate. The rate of cooling produced depends upon the temperatures, mass and shape of the steel, the temperature, volume, inherent characteristics, and speed of circulation of the quenching medium or speed of movement of the steel being quenched.

With reference to the effect of the inherent characteristics of the quenching medium, it may be said that when a piece of hot steel is immersed in a liquid such as water, oil, or aqueous solutions, the liquid coming into direct contact with the hot steel is first vaporized. Heat is absorbed by raising the liquid to the boiling point and then by converting it into a vapor. Both the specific heat and the latent heat of vaporization of the liquid are factors in determining the speed of cooling produced. The vapor thus formed usually recondenses and gives up its heat before it reaches the surface of the bath. As the conductivity of the liquids is relatively low, conduction of heat through the quenching bath probably is a minor factor in determining the speed of cooling. The relative merits of different media are discussed in another section of this article.

With any given quenching medium, the speed of cooling may be varied by changing the speed of movement of the hot steel or the speed of circulation of the quenching medium.

The motion of the steel may vary from zero to any desired rate. Small articles are frequently quenched by allowing them to drop through the bath to the bottom of a basket or onto a conveyor in the bottom of the quenching tank. In the former case it is preferable that the distance to the bottom of the basket be great enough so that the pieces being quenched will be relatively cool before they reach the bottom. When conveyors are used the steel is kept in motion after it falls upon the conveyor. In any case, however, the steel should not be allowed to pile up in the basket or on the conveyor before it is properly cooled. A variation of the type of motion produced by gravity consists in rolling or skidding the work down rails or plates through the quenching bath. This produces a slower speed of travel but increases the length of time that the work is in motion before reaching the bottom.

Small pieces held by hand tongs and larger ones held by hoists are frequently kept in motion until reasonably cool. Moving conveyors are employed for pieces varying in size from that of small bolts to automotive front axles. A variation of the conveyor method of producing motion consists of a rotating screen barrel with a worm inside which keeps the work constantly tumbling over and advancing forward. This is particularly advantageous in handling small parts on a quantity production basis.

The simplest type of circulation of the quenching media is that produced automatically by the action of the hot steel in vaporizing and heating the bath in its immediate vicinity. The tendency is for the vapor to rise from the top of the steel and for fresh liquid to rush in to the bottom. The speed of such circulation depends upon the characteristics of the quenching medium. At best this is likely to produce nonuniform cooling. If the design of the piece is such as to allow the formation of vapor pockets, the quenching becomes even less uniform.

The next and most common type of circulation consists of the flow of the liquid into, through, and out of the tank. Usually the inlet is near the bottom and the outlet near the top of the tank. The rate of circulation thus produced is usually not extremely rapid, but is nevertheless quite an important factor in governing the speed of quenching.

Another type of circulation of the quenching medium is effected by means of mechanical agitators or propellers, which produce rapid circulation of the liquid

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within the quenching tank. This may be arranged so as to provide a rapid flow of the medium around the piece being quenched. This may supplement the flow of liquid into and out of the tank.

Another and most effective method of controlling circulation is involved in what is commonly known as "pressure quenching". This method forcing the quenching medium directly against the steel under pressure. Either open or submerged pressure jets may be arranged so as to produce either uniform cooling or very rapid cooling of some particular locality. Specially designed pressure quenching fixtures frequently solve the problem of uniform quenching of parts of intricate design.

In selecting or designing quenching equipment some attention must frequently be given to minimizing warping and distortion, which results from nonuniform cooling. Any method which produces more uniform cooling will help minimize warping. For example, a shaft which is revolved in a horizontal position in the quenching bath will warp less than one which is held stationary in the same position. Similarly, a properly designed pressure quenching fixture will produce less warping than free hand quenching.

Another method of minimizing warping and distortion consists in mechanically holding the article during quenching. As an example of this type of equipment, may be mentioned the quenching machine commonly used in the hardening of automotive bevel ring gears. This consists essentially of an expanding mandrel and a set of perforated dies which hold the gear under pressure during quenching. The quenching medium is forced under pressure to all parts of the gear during quenching.

Volume of Quenching Medium—It is obvious that heat removed from the steel being quenched is absorbed by the quenching medium, and consequently causes an increase in the temperature of that medium. As an increase in the temperature of the quenching medium produces a different speed of cooling, it is usually desirable to control the temperature of the quenching medium within certain desired limits.

Rise of temperature above the allowable maximum can be prevented only by bringing a sufficient volume of the quenching medium into close enough proximity to the steel to be effective in removing heat. This statement holds true regardless of whether the circulation is natural or produced by artificial means. (See the following discussion of "Cooling the Quenching Medium".)

Minimum Volume of Quenching Medium—The theoretical minimum volume of quenching medium which must come within the effective proximity of the steel in a given length of time may be calculated with the use of the following formula:

$$\frac{W' \times SH' \times (T' - T'')}{SH'' \times W'' \times TR} = \text{cu.ft. of quenching}$$

medium which must come within an effective proximity of the steel in a given time.

In which:

W'	=	Weight of material quenched.
SH'	=	Mean specific heat of material quenched.
T'	=	Temperature of heated material.
T''	=	Temperature of material at time of removal from quenching tank.
SH''	=	Specific heat of quenching medium.
W''	=	Weight per cu.ft. of quenching medium.
TR	=	Allowable temperature rise of quenching medium.

Particular attention is called to the statement that this volume must come within the effective proximity of the steel. For example, this formula can be used for calculating the size of a tank for batch quenching without forced circulation, only in case all of the liquid in the tank comes into close enough proximity to the steel to absorb heat, or in case the rate of addition of hot steel to the tank is slow enough so that the heat absorbed will be conducted or conveyed to other portions of the tank. In this connection, it must be remembered that the quenching medium in the bottom of the tank below the level to which the hot steel is submerged will remain cold, and consequently, cannot be considered in the effective volume of the tank.

In applying this formula to the calculation of volume to be delivered by pumps to quenching tanks, it must also be remembered that all of the volume delivered to the quenching tank may not be effective in removing heat from the steel.

Consequently, it is recommended that the above formula for theoretical mini-

mum volume be multiplied by a liberal safety factor in calculating size of tanks and capacities of pumps. It is a safe recommendation that pumps and tanks should be figured oversize rather than undersize.

Cooling of the Quenching Medium—Method of cooling the quenching medium depends very largely upon the type and quantity of work to be handled. The various methods of cooling may be classified briefly as follows:

1. *Tank Cooled by Direct Radiation*—In cases where the production is very small, a simple tank without any special means of circulating or cooling may be sufficient. The tank should be quite large in proportion to the quantity of heat to be removed per unit of time. Cooling is purely by radiation from the surface and the walls of the tank. This type of tank is frequently used in tool rooms, which do a limited amount of hardening of small tools each day. In case the quenching medium is oil, the temperature should be checked occasionally and not allowed to become too high as there is a decided fire risk if the temperature of the oil approaches its flash point.

2. *Cooling of the Quenching Medium in the Tank Without Forced Circulation*

(a) The method of surrounding the quenching tank with a large water jacket with or without circulation of the cooling water has the advantage of low initial cost. The rate of transmission of heat from the tank to the water jacket is relatively low. The larger the tank in proportion to the wall surface, the lower will be its efficiency. Consequently, this design is limited to small installations.

(b) The quenching tank may be supplied with coils through which cold water circulates. The efficiency of this method depends upon the cooling surface of the coils in proportion to the volume of the tank. Efficiency is relatively low, but may be somewhat greater than that given under 2-a. This design is also limited to comparatively small installations.

(c) The quenching tank may be equipped with coils through which is circulated an externally cooled liquid, such as water or brine. This method is somewhat more efficient than those previously mentioned, but is more expensive as it introduces a pump and an external cooling system.

3. *Circulation of the Quenching Medium Between the Quench Tank and an External Cooling System.*

This type of equipment may be subdivided according to the type of external cooling system employed.

(a) A large storage tank which may or may not be supplied with cooling coils requires a large quantity of quenching medium in the storage tank in proportion to the size of the quenching tanks. If the storage tank is not provided with cooling coils, the temperature attained by the liquid will depend somewhat upon the surrounding temperatures. This method has the advantage of simplicity, and may be advantageous where land values are low, and large storage tanks or cisterns can be built economically.

Aside from its cooling function, a storage tank acts as a common reservoir for all of the quenching tanks in the hardening room, and permits drainage of at least a portion of these tanks and utilization of the oil in the other tanks.

(b) Air cooled coils or pipes may be supplied through which the quenching medium is circulated. This requires a large surface area, as the rate of transmission of heat from the pipes to the air is relatively low. The final temperature of the quenching medium is limited by the air temperature.

(c) The method of spraying or aerating the quenching medium is usually employed in conjunction with cooling coils or tanks. This is the most efficient of the air cooling systems, as the liquid when divided into a spray offers a large cooling surface in proportion to its volume. This method may be open to the objection of a fire hazard if used in the cooling of hot oil. Space and location of this type of equipment must be carefully considered.

(d) Tanks may also be equipped with an external cooling system of tubes, through which the quenching medium circulates. The efficiency of this method will depend somewhat upon the ratio of the cooling system of the tubes to the volume of the liquid passing through them. When used in a shell and tube type unit with water as the cooling medium, the shell side using the water must be accessible for cleaning. If the shell side becomes covered with scale, the efficiency of

the unit is decreased. It is advisable, therefore, to use a water which produces the minimum amount of scale, or to resort to frequent cleaning. Careful design of the cooling unit is recommended.

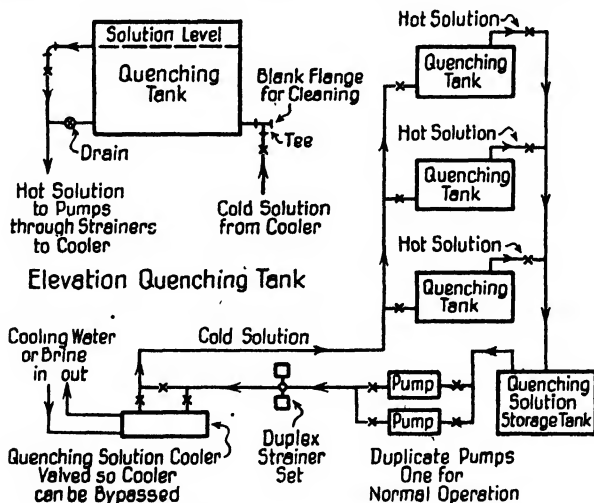
(e) Another external cooler consists of tubes over or around which the quenching medium is circulated. When such units are properly designed, their efficiency should be relatively high as the quenching medium passes in a thin film over a comparatively large cooling surface. Where water is used as the cooling medium, it is necessary that the cooler be designed so as to permit easy removal of scale from the interior. This method has the advantage of efficiency and compactness, but the disadvantage of a higher initial cost.

(f) There are a number of specially designed commercial coolers, which usually involve one or more of the cooling principles previously mentioned. These usually are designed for a close approach between the temperatures of the quenching medium and the cooling liquid. They have an advantage of compactness and efficiency, but the disadvantage of higher initial cost.

(g) When water is used as the coolant, the lowest temperature which can be attained by the quenching medium will be slightly higher than that of the water. When still lower temperatures are desired, it is necessary to use a refrigerating system. With proper design, any desired temperature may be produced by refrigeration. This method may also be used for cooling the quenching liquid to temperatures above that of tap water. The refrigerating system has the advantage of small size and maximum efficiency, but the disadvantage of high initial cost and comparatively high cost of operation and maintenance.

Safety Precautions—When oil is employed as the quenching medium, proper precautions should be taken to minimize the fire risk. The temperature of the oil in the quenching tank should never be permitted to approach the flash point. Fig. 1 shows duplicate pumps and strainers in the circulating system. This is very important as any breakdown of the circulating system might result in a serious fire.

In case of fire, the circulation of the oil should be kept up, or if possible increased in order to lower the temperature of the oil below its flash point. Oil fires start slowly and are usually readily extinguished if the action is prompt. It is often possible to extinguish them by merely stirring the oil in the quenching tank.



Note: Quenching Solution Storage Tank and Pumps to be located at lower elevation than other units.

Fig. 1—Typical piping arrangement showing a plan view of a battery of quenching tanks with external quenching solution cooler.

Smother covers, which can be quickly applied, are very satisfactory for small tanks and have been used to some extent even with large ones. A fire hose or a sprinkler system delivering water into an oil fire may spread the fire. Chemical

extinguishers are preferred. The chemical should be shot just above the surface of the burning oil—not into the oil—as the rapid vaporizing of the chemical beneath the oil might also spread the fire.

In designing an external cooling system, the specific gravity, viscosity, and thermal conductivity of the quenching medium should be taken into consideration. These have an effect upon the heat transfer rate obtained for any given solution and upon the amount of cooling surface required. The quantity of quenching liquid handled per unit of time, the range of temperature to which it is to be cooled, the amount and temperature of cooling water to be used, and the friction loss of both liquids which may be permitted, are also factors governing the design of the cooler.

Fig. 1 shows a typical layout of quenching tanks, and a cooling and storage system. This is given to show general principles only. The selection of quenching and cooling equipment will depend upon the quantity and type of work to be handled, value of land or floor space, and the cost of installation, operation and maintenance.

Quenching Media

By Howard Scott*

Requirements of Quenching Liquids Imposed by the Work to be Hardened—It is assumed that the function of the quenching is to produce martensite and hardening implies the formation of this constituent. Whether or not hardening occurs with a particular quench depends on the composition of the steel as well as on that of the quench. In recognition of the steel composition effect, it is necessary to distinguish at least between shallow and deep hardening steels in the discussion of quenching media. The shallow hardening steels are those of low or no alloy content while the deep hardening steels have a substantial content of alloying elements which increase penetration of hardening, notably chromium, manganese, nickel and molybdenum.

The fundamental property distinguishing shallow from deep hardening steels is the critical cooling rate. It is the slowest cooling rate measured at about 1020°F. at which a completely martensitic microstructure can be obtained. The temperature

specified is that of maximum rate of reaction in eutectoid carbon steel established by the Bain "S" curve.¹ The critical cooling rate for pure iron-carbon alloys when fine grained is extremely high, so high that effective hardening is impracticable. Even in plain carbon steels it is high, ranging from 126-360°F. per second. Evidently then an extremely fast quench is required for the hardening of shallow hardening steels.

Water under favorable conditions provides the surface cooling rate necessary for the hardening of carbon steels. It is in the neighborhood of 1800°F. per second. Surface cooling at this rate produces rates within the steel close to the maximum values theoretically possible of attainment; so there is little room for improvement in the cooling rate attainable with water. There are, however, other characteristics of water amenable to considerable improvement which are discussed later.

To cool as fast as indicated over the entire surface of the work is a difficult art. The success of the quench is determined within the first few seconds of immersion. If the cooling rate does not exceed the critical rate at any one point martensite will not form there. This constitutes a soft spot and soft spots seldom can be tolerated. Consequently, the need for extreme rapidity of surface cooling dominates all other factors in the hardening of shallow hardening steels.

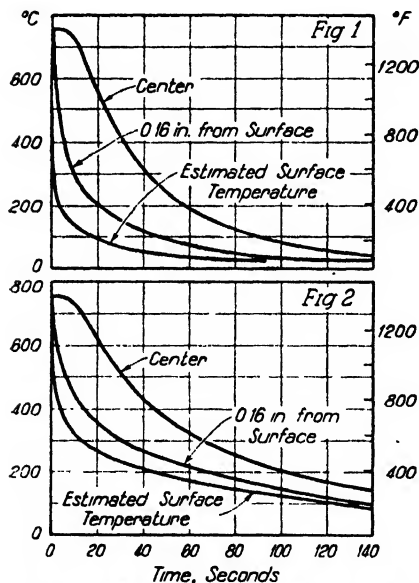


Fig. 1—Observed cooling curve of center and of a point 0.16 in. from the surface of a long austenitic steel cylinder 2.00 in. dia. during quenching in agitated water.

Fig. 2—Observed cooling curve of center and of a point 0.16 in. from the surface of a long austenitic steel cylinder 2.00 in. dia. during quenching in agitated oil.

A necessary consequence of fast surface cooling is a high temperature gradient from surface to center. This gradient may exceed 70% of the temperature range, Fig. 1. It produces severe distortion in all but simple, symmetrical shapes having a low ratio of length to diameter or thickness. Shallow hardening steels, therefore, cannot be used in complicated shapes where distortion is objectionable. Furthermore, there is no possibility of changing this situation by choice of quenching medium if full surface hardening is required.

Despite the admirable properties of carbon steels, which include a low price,

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Prepared for the Subcommittee on Quenching Media. The membership of the subcommittee was as follows: A. L. Boegehold, Chairman; I. N. Zavarine, G. T. Williams, R. B. Queneau, and Howard Scott.

they cannot be used for complicated shapes where distortion must be avoided. In this case water quenching must be abandoned and a less active quench used which reduces materially the temperature gradient during quenching, Fig. 2. Certain oils perform this function admirably but are incapable of hardening shallow hardening steels of substantial size. A change in steel composition is therefore required with a change from water to an oil quench.

Oil quenching introduces entirely different problems from those of water quenching. Cooling rate gradients are no longer high so a completely martensitic surface shell can seldom be obtained over a fully pearlitic core. Usually there is considerable martensite at the center when the surface is fully hardened. If hardening is incomplete at the surface, there exist soft spots which may not be easily detected by a hardness test but which lower the toughness otherwise obtainable at the same hardness in their absence.

Since the cooling rate is slower the larger the section, the alloy content must be increased with increase in thickness of the section. Table I gives the cooling rates at the center of long cylinders during quenching in several media when the center temperature is 1022°F. relative to that of 1 in. dia. cylinder quenched in agitated water, rate for which is 101°F. per second.*

Table I
Relative Cooling Rates in Several Quenching Media

Quenching Medium	Relative Cooling Rate for Diameter of:		
	1 in.	2 in.	3 in.
Fastest theoretically attainable.....	1.23	0.30.	0.14
Agitated water	1.00	0.27	0.13
Agitated oil	0.48	0.18	0.093
Air stream	0.032	0.0157	0.0102
Still air	0.0152	0.0075	0.0048

Table II
Cooling Rate of 4 mm. Diameter Nichrome Ball Over the Temperature Range 1328-1022°F. During Quenching in Various Media from 1580°F.*

Quenching Medium	Cooling Rate Relative to that for Water at 65°F.*	
	1328-1022°F.	At 392°F.
Aqueous solution 10% LiCl.....	2.07	1.04
Aqueous solution 10% NaOH.....	2.06	1.36
Aqueous solution 10% NaCl.....	1.98	0.98
Aqueous solution 10% Na ₂ CO ₃	1.38	1.09
Aqueous solution 10% H ₂ SO ₄	1.22	1.49
Water at 32°F.....	1.08	1.02
Water at 65°F.....	1.00	1.00
Aqueous solution 10% H ₂ PO ₄	0.99	1.07
Mercury	0.78	0.62
Sn ₃₀ Cd ₇₀ at 356°F.....	0.77	0.009
Water at 77°F.....	0.72	1.11
Rape seed oil.....	0.30	0.055
Trial oil #6.....	0.27	0.045
Oil P20	0.23	0.055
Oil 12455	0.22	0.022
Glycerin	0.20	0.89
Oil 20204	0.20	0.13
Oil, Lupey light.....	0.18	0.20
Water at 122°F.....	0.17	0.95
Oil 25441	0.16	0.18
Oil 14530	0.14	0.022
Emulsion of 10% oil in water.....	0.11	1.33
Copper plates	0.10	0.067
Soap water	0.077	1.16
Iron plates	0.061	0.011
Carbon tetrachloride	0.055	0.34
Hydrogen	0.050	0.011
Water at 166°F.....	0.047	1.31
Water at 212°F.....	0.044	0.71
Liquid air	0.039	0.033
Air	0.028	0.007
Vacuum	0.011	0.004

*Cooling rate for water at 65°F. is 3260°F./sec. over the range 1328-1022°F. and 810°F./sec. at 392°F.

With an oil quench the temperature gradients are considerably lower than with water, Fig. 1 and 2. The residual stresses determined by these gradients are also lower when hardening is complete at the center or nearly so. Though less intense than those of water hardening steels, these residual stresses are more dangerous because they are usually tensional at the surface of the work.

Residual stresses are "set" during the hardening transformation, A_r , but do not reach maximum intensity until the work is cold. It has been shown⁴ that their final magnitude diminishes with speed of cooling through the hardening transformation which starts under 750°F. and usually around 400°F. Thus slow cooling of deep hardening steels is important in this temperature range just as fast cooling is in the high temperature range where reaction velocity is high.

The advantage of slow cooling through the hardening transformation is easily demonstrated by quenching two 1 in. rounds of deep hardening tool steel in oil for 20 seconds then removing and cooling one in air, the other in water. The water cooled piece will crack explosively while the air cooled piece will not crack even though held without tempering.

Quenching in oil does not entirely prevent distortion. When the degree produced by oil quenching is objectionable, recourse is taken to air hardening. The cooling rate in air is much slower than in oil or water (Table I) so an exceptionally high alloy content is required. This means that a high price is paid for the advantage gained both in terms of metal cost and loss in machinability, though it may be well justified when applied to expensive tools. In this case danger of cracking is negligible.

Liquid metals and salts are also used as quenching media. A cadmium-tin alloy at 355°F. is intermediate between oil and water, as regards hardening ability and much superior to oil as regards residual stress generation. This is indicated by the position of this alloy in the left hand column of Table II and the low value in the right column relative to that in the left.

Table III

Maximum Sizes of Various Steels That Will Harden to C-50 Rockwell at the Center on Quenching in Oil and Water Together with Corresponding Critical Cooling Rate¹¹

S.A.E. No.	Grain Size	Maximum Diameter in Inches for		Cooling Rate at Center, °F./sec.
		Oil Quench	Water Quench	
1050	5-6	0.30	0.70	198
1045 + 0.2% Cr	6-8	0.40	0.90	134
T1340	5-8	0.70	1.20	76
5140	5-8	0.92	1.55	50
3145	5-6	1.15	1.80	38
4140	6-8	1.50	2.15	29
X3140	6-8	2.50	3.35	13
4340	....	3.40	5.00	6

Considerable variation from these figures is possible for each steel listed depending upon the grain size, method of manufacture, and composition. Cooling rates at center of rounds are those given by Scott¹² for water and oil quenching. Variation in severity of quench due to change of oil or water will change the above figures.

The major practical questions in connection with quenching media still remain. Will a particular size and composition of steel harden satisfactorily in water or oil? Data are not yet available to give a comprehensive answer, but Table III from a paper by Jominy and Boegehold¹¹ provides information on several important steels. In using such data it must be realized that there is a considerable variation between steels of the same nominal composition.

Liquids for Quenching Shallow Hardening Steels—Shallow hardening steels require extremely rapid surface cooling in the quench particularly in the temperature range around 1020°F. So far as is known a submerged water spray will give the fastest and most reproducible quench practicable. Such a quench, however, is distinctly limited in application to simple short objects which are not likely to warp. Because of the difficulty in obtaining symmetrical flow of the water relative to the work, the spray quench is highly conducive to warping. The ideal quench is one which will give the required surface cooling without any agitation of the bath.

It has been shown that concentrated sulphuric acid is a close approach to this ideal.⁵ Sulphuric acid is, however, too dangerous a liquid for practical use. Ordinary

tap water without agitation is a poor substitute which will not harden consistently with freedom from soft spots. The addition of ordinary salt (sodium chloride), however, greatly improves the performance of water. The manner in which salt improves the quenching properties of water can be seen clearly from the observations of Pilling and Lynch⁴ on various liquids and from Table V.

By taking cooling curves on a small specimen during quenching, Pilling and Lynch determined how the surface cooling power of the liquid changed with the surface temperature of the piece. Their observations are extremely significant in that they show three distinctive mechanisms of heat dissipation which have been verified by Speith and Lange.¹² Fig. 3 is a typical curve showing the three stages. These three stages of cooling have been described by Scott³ as follows:

Stage "A"—Vapor Blanket Cooling—In this, the first stage, a thin stable vapor film surrounds the hot metal. Cooling is by conduction and radiation through the gaseous film and is therefore relatively slow.

Stage "B"—Vapor Transport Cooling—Termination of the "A" stage is marked by wetting of the metal surface. Vapor forms copiously in bubbles and is carried away by gravity and convection currents to condense in cooler surrounding liquid. This is the fastest stage of cooling.

Stage "C"—Liquid Cooling—The "B" stage ends as the surface temperature of the metal approaches the boiling point of the quenching liquid. Vapor no longer forms so cooling is by conduction and convection and the temperature difference is greatly decreased. This mode of cooling is slower than that of the "B" stage.

Cooling in the "B" and "C" stages is in fair accord with Newton's law of cooling, that is the cooling rate is proportional to the surface temperature, which holds closely for short temperature ranges.³ In the "A" stage, however, cooling is at a nearly constant rate, which rate decreases somewhat with increase in the bath temperature.

Zavarine has noted from high speed photographs that rate of bubble collapse is relatively slow in the "A" stage and extremely fast in the "B" stage, of course vanishing in the "C" stage. Also that crystals of salt are precipitated momentarily during quenching in brine.

There has been much debate concerning the fundamental properties of liquids determining their quenching power. Those mentioned include: Thermal conductivity, viscosity, specific heat, heat of vaporization. Evidently which property is dominant depends on the stage concerned. Certainly boiling point is a major factor in the "A" stage, heat of vaporization in the "B" stage, and thermal conductivity in the "C" stage. Viscosity also contributes to cooling power both in the "B" and "C" stages. Each stage has an important part in determining the success of a quench. No distinction has been made between the "A" and "B" stages in the data of Table II, the left hand column representing a combination of both stages though the right column represents "C" stage cooling only. As a consequence of this overlap, water at 120°F. for example is placed below certain oils though its cooling rate in the "B" stage is just as fast as that of the LiCl solution. The three stages have been sharply distinguished in Table V.

The vapor stage, "A," is of most concern in water solutions. Cooling is slow in it and if it persists for more than a few seconds transformation will occur at A_r , producing soft spots. To avoid this occurrence the vapor stage must be suppressed or nearly so. Its duration may be measured in time units on the quenching curves of Pilling and Lynch giving a quantitative measure of the extent to which it is suppressed, Fig. 4. This figure shows that the duration of the vapor stage in water and water solutions increases rapidly with bath temperature. Hence the first rule of quenching is: *Keep water base quenching liquids cold, preferably under 70°F.*

Fig. 4 also shows clearly why salt is an advantageous addition to water. It reduces materially the duration of the vapor stage particularly at elevated temperatures. The liquid adjacent to the work is of course much above the average bath

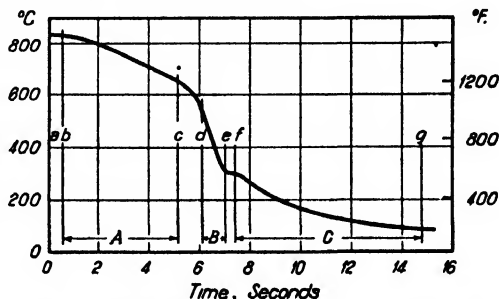


Fig. 3—Typical cooling curve for the center of a small cylinder during quenching in still water at 137°F. It illustrates the three stages of surface cooling.³

temperature. From this viewpoint the best concentration is a saturated solution, about 26%, but there are objections to so high a concentration mentioned presently. A commonly used concentration is 10%, but under 5% is not recommended.

Other inorganic compounds are also effective in suppressing the vapor stage, calcium chloride and sodium hydroxide being used. As a matter of fact, most of the inorganic salts have a favorable effect in diminishing the duration of the vapor stage. A solution of common or rock salt in water of a concentration between 5 and 15% is a great improvement over pure water and is widely used. The concentration of salt in the bath may be checked with an ordinary hydrometer of suitable range. Relations between salt concentration and density measured by hydrometer are given in Table IV.

The presence of some other soluble materials in water is decidedly detrimental. Soap particularly extends the duration of the vapor stage cooling and therefore acts in the same manner as an increase in temperature of water, Fig. 4. It can easily overcome the benefit conferred by a salt addition and cause the formation of soft spots on quenching in brines. Soft spots form on carbon steels even when quenched in tap water at 70°F. Hence the rule: *Avoid contamination with soap of aqueous quenching liquids.*

Once the vapor stage, "A," is passed or suppressed, stage "B" cooling, in which water has its phenomenal cooling power, commences. Cooling power in this stage is not reduced materially by increase of bath temperature, but is reduced appreciably by salt additions. In fact a saturated solution of sodium chloride in water (about 25%) is no better than tap water at the same temperature, though the experiments recorded in Table V failed to disclose this fact. The effect at a 10% concentration, however, is small and more than offset by contraction of the "A" stage.

Liquids for Quenching Deep Hardening Steels—Deep hardening steels are used in order that a fully martensitic structure may be obtained with an oil quench and therefore without excessive distortion.

The vapor film stage of cooling, "A," is less important in oil than in water quenching. Actually, the vapor stage may persist longer, Table V, but is not harmful unless exceptionally long because the rate of cooling is faster in this stage with oil than with water, and the critical cooling rate of the steel is properly used with an oil quench. The duration of the vapor stage is longer the lower the boiling point of the oil (Table V) so some bottom limit should be placed on the boiling point of the oil used. Of course the boiling point of oil is a rather indefinite quantity and has to be defined arbitrarily.

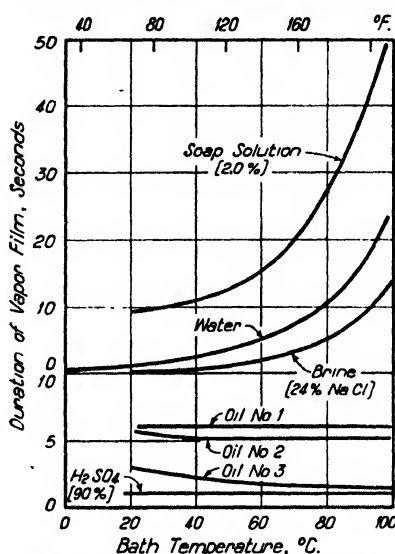


Fig. 4—Duration of the vapor film stage of surface cooling during quenching in several liquids.⁶

Table IV
Relation of Brine Density to Salt Concentration

NaCl, %	Lb. Salt per Gal. of Water	Density at 68°F.	Salinometer Reading	Degrees Baumé
0	0.0	1.000	0.0	1.00
5	0.43	1.039	18.9	4.8
10	0.89	1.071	37.8	9.6
15	1.39	1.108	56.6	14.2
20	1.92	1.148	75.6	18.7
25	2.44	1.189	94.5	23.1

The boiling points of the oils listed in Table V are so high that moderate increases in oil temperature have little effect on the duration of vapor film cooling. Consequently, oils, contrary to water solutions, can be used while warm without danger of incomplete hardening and with advantage in some respects. The cooling power of warm oil in the "B" stage is actually higher than that of cold oil. It is

undoubtedly due to lowered viscosity which permits more rapid movement of vapor carrying heat away from the metal surface. A real advantage of using warm quenching oil, however, arises from consideration of residual stresses.

There is danger of cracking deep hardening steels by fast cooling into the hardening transformation as already shown. This transformation usually occurs during cooling in the "C" stage. If then cooling, in this stage, can be slowed down materially, there is less danger of cracking. Referring to Table V, cold oil has an advantage over water in this respect. The cooling rate in the "C" stage of oil is about 1-10 of that in the "B" stage while with water the ratio is about 1-6.5. However, the major advantage of oil is that its temperature can be raised considerably without bad effects, thereby lowering decidedly the cooling rate of the work when approaching the hardening transformation.

Table V

Cooling Rates at Center of $\frac{1}{4}$ in. Dia. Cylinder During Quenching in Still Liquids at 104°F. Showing Variation in Cooling Action with Surface Temperature of Pieces.*

Quenching Liquid	Boiling Point, °F	Duration of Vapor Film, Sec.	Relative Cooling Rate*— in Stage:		
			"A"	"B"	"C"
Tap water, up to 104°F.....	212	3	0.10	1.00	0.16
Brine (24% NaCl).....	221	1	...	1.00	0.15
Sulphuric acid (90%).....	504	1	...	0.96	0.09
Soap solution (2%) up to 104°F.....	...	11	0.08	...	0.15
Oil #1	712	6	0.16	0.36	0.035
Oil #2	756	5	0.17	0.48	0.042
Oil #3	860	2	...	0.27	0.027

Physical Properties of Oils

	#1	#2	#3
Flash point, °F.....	370	399	581
Fire point, °F.....	419	466	646
Boiling point, °F.....	712	756	860
Density	0.882	0.912	0.916

*Cooling rates in "A" stage taken at 1472-1292°F.; in "B" stage at 1022°F.; and in "C" stage at 392°F.

Caution must be exercised in using warm quenching oil. Its temperature should not be so high that it flashes or burns after work is immersed or is dangerous to workmen using it. These considerations are the basis for the rule:

Keep quenching oil warm, preferably between 90 and 140°F.

This rule is particularly important when hardening tool steels which, being high in carbon content, are highly susceptible to cracking. Their hardening transformation, however, occurs at a low temperature, so much is gained by a small increase in bath temperature. If this expedient is insufficient to prevent cracking the work may be removed just before the start of the hardening transformation and cooled in air. Whether or not transformation has started can be determined with a permanent magnet, the work being completely nonmagnetic before transformation if completely hardened by the quench.

So far only generic qualities of oils have been considered. To be specific about the selection of an oil among the numberless compositions available is difficult. The only practical way of identifying oil compositions is by their physical properties and only a few investigators of cooling characteristics have recorded identifying properties, notably those whose data is given in Tables V and VII. Their standard tests are still probably inadequate to assure reproduction of the major properties required in quenching. A list of standardized tests of oils is given in Table VI and is probably sufficiently inclusive to assure duplication of good quenching properties found in a particular oil.

The standard tests are also important with regard to secondary requirements of quenching oils. Low viscosity assures free draining of oil from the work and therefore low oil loss. A high flash and fire point assure a high boiling point and reduce the fire hazard which is increased by keeping the oil warm. Low pour test assures ample viscosity when cold. A low carbon residue suggests stability of properties with continued use and little sludging. The steam emulsion number should be low to assure low water content, water being objectionable because of its vapor film forming tendency and high cooling power. A low saponification number assures that the oil is of mineral base and not subject to organic deterioration of fatty oils

which gives rise to offensive odors. Viscosity index is a valuable property for maintenance of composition.

Tests for these properties are suggested however only as a means for maintaining the composition of an oil found to be satisfactory by experience. Continuity of properties is perhaps the most important requirement for quenching oils. Another is that sludge shall not deposit on cooling coils. Films of salt on the work as when quenching from fused cyanide bath are detrimental to oil. In this case use of a straight mineral oil is indicated.

Table VI
Standard Tests for Oil Which Are Significant with Respect to Its
Quenching Behavior

Test	A.S.T.M. Standard Method Number
Specific gravity	D158-28
Viscosity	D88 -36
Flash point	D92 -33
Fire point	D92 -33
Pour test	D97 -34
Carbon residue	D189-36
Steam emulsion	D157-36
Saponification number	D 94-36
Viscosity index (See Reference #9)	

Table VII
Cooling Power and Other Properties of Various Oils*

Quenching Medium	Cooling Rate Relative to Water	Sp. gr. at 60°F.	Flash Point, °F.	Fire Point, °F.	Absolute Viscosity at 68°F., Poises	Approx. Viscosity at 100°F., Saybolt Universal
Prepared ¹ oil No. 1.....	0.44	0.862	365	405	0.421	110
Prepared ¹ oil No. 2.....	0.35	0.874	375	415	0.417	110
Transformer oil	0.17	0.869	311	360	0.218	75
Machine oil	0.22	0.909	405	464	1.29	250
Paraffin oil	0.29	0.879	325	370	....	...
Fuel oil	0.36	0.856	205	219	....	...
Palm oil	0.15	....	435	486	0.449 ²	220
Rapeseed oil	0.22	0.874	379	444	....	250
Castor oil	0.29	0.963	565	640	10.43	1500
Cottonseed oil	0.36	0.925	610	680	0.795	175
Olive oil	0.37	0.917	590	680	0.800	200
Lard oil	0.19	0.917	565	685	0.836	180-200
Fish oil	0.31	0.933	401	446	0.698	130
Sperm oil	0.33	0.885	500	581	0.374	110
Neatsfoot oil	0.33	0.922	500	621	1.25	230-270
100% A ³	0.26	0.864	360	410	100	65
95% A + 5% B ⁴	0.39	....	....	....	....	....
90% A + 10% B	0.41	....	....	....	....	....
85% A + 15% B	0.42	....	....	....	....	....
60% A + 40% B	0.35	....	....	....	....	....
30% A + 70% B	0.32	....	....	....	....	....
100% B	0.29	0.897	534	610	3600	1200

*Cooling power is measured by the cooling rate of a ½ in. dia. cylinder of 1% C steel when it has cooled to 1328°F. from 1607°F. while in still oil. Values of cooling rate are relative to that for quenching in still water which is 356°F./sec = 1.00.¹⁰

¹These are probably oils with a mineral base and contain 3.3% fatty acid.

²Taken at 95°F.

³Pa. pale neutral oil—viscosity 65 at 100°F. (Saybolt)—flash point 360°F.

⁴Pa. heavy residuum crude oil, steam refined—viscosity 1200 at 100°F. (Saybolt)—flash point 534°F.

Efforts have been made to secure quenching characteristics in water base liquids equivalent to those of oil. This is an admirable objective but so far has been entirely unsuccessful. Oil cooling rates in particular temperature ranges can be secured, but not throughout the whole temperature range of quenching and therein lies the trouble. Scott,¹¹ for example, shows that a mixture of glycerin and water will give a cooling rate in the "B" stage which is the same as that of a popular proprietary quenching oil. The cooling power of this liquid in the "C" stage, how-

ever, is much faster than that of oil, which condition is highly objectionable from the viewpoint of residual stresses. The same objection applies to solutions of ethylene glycol and sodium silicate in water. Also, the duration of the "A" stage in all of these liquids is increased by the presence of water which endangers completeness of hardening.

Emulsions of oils in water also have been used as quenching media. Their characteristics are even worse than those of the solutions just mentioned. The "A" stage cooling is greatly extended and the "C" stage is practically as fast as water. This reversal of the ideal relations between the stages is shown clearly in Table II. Thus there is no obvious prospect of a water containing substitute for oil being developed.

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Constitution Diagrams

By J. E. Schoen*

A metal may exist in at least three distinct states: vapor, liquid, or solid. In addition to these three general states, many of the common metals will appear in more than one solid form thus increasing the number to more than three. These states are usually called phases and may be illustrated by a simple substance such as water, the liquid phase of H_2O , steam, the vapor phase, and ice, the solid phase. Each of these phases exists throughout a certain range of temperature, with the solid at the lower end of the temperature scale, followed by the liquid and finally at the higher temperature by the vapor. In the case of ice, when the pressure is atmospheric, it is well known that melting occurs at $32^\circ F$. producing water which in turn boils at $212^\circ F$. forming steam. These temperatures are definite (with constant pressure) and are easily obtained experimentally due to the rather large heat absorptions when either the ice melts or the water vaporizes because during these changes of state the temperature remains constant. In the study of metals the vapor state and the effect of pressure on the temperatures at which these phase changes occur are relatively unimportant and will be disregarded.

However, while the temperature at which a phase change occurs is definite for one metal it can be either lowered or raised by the addition of a second metal or metalloid. Moreover, the freezing process no longer takes place at a constant temperature (except in certain specific instances explained later) and further changes may occur all the way down to room temperature, long after the resulting mixture or alloy has become solid. These changes will vary with increasing amounts of the second metal and if we plot the temperatures at which phase changes take place on a graph whose vertical axis is temperature and whose horizontal axis is concentration or composition and in addition connect these points by smooth lines we produce

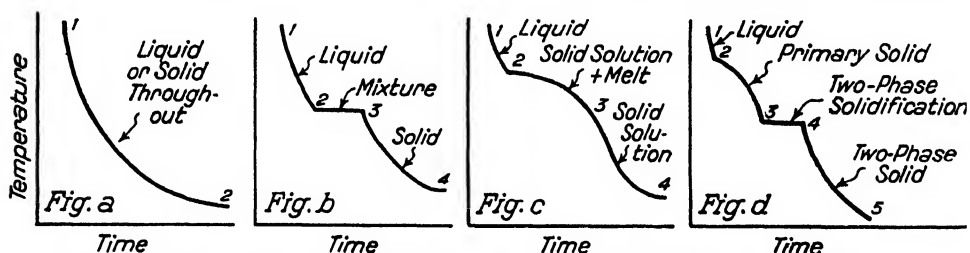


Fig. 1a—Typical cooling curve for substance that does not go through change of state.

Fig. 1b—Cooling curve for pure metal and stable compounds from the molten condition to solid state.

Fig. 1c—The cooling of an alloy in which metals remain dissolved (solid solution) in each other when solid.

Fig. 1d—The cooling of an alloy where crystals of some primary phase solidify first followed by the simultaneous freezing of two phases from the melt.

a diagram called the equilibrium diagram or constitution diagram of the system.

In many alloy systems these changes of state take place rather slowly, particularly in the solid state. Therefore since the diagram must always represent conditions of equilibrium or balance, it follows that the phase relationship is seldom valid for any ordinary heat treating process but is approximated most closely by very slow cooling.

When an alloy is quenched in water or oil, the phases tend to remain in the state indicated by the diagram at the temperature from which they are quenched. If this state is not maintained some transitional state intermediate between this and the normal one at room temperature will be obtained. These transitional states, relatively unstable, are not shown by the equilibrium diagram.

The construction of these diagrams is based primarily on changes in the cooling or heating rates of a series of alloys whose compositions constitute a cross section of the system. These changes are best shown in the accompanying cooling curves.

In Fig. 1a the substance goes through no change of state from 1-2, and the rate of cooling which is extremely rapid at the higher temperature is retarded as the temperature of the material falls; the last few degrees drop requiring a consid-

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erable period of time as the material approaches the temperature of its surroundings. This type of curve is typical of any substance whether molten or solid so long as the loss of heat is a sensible one only and is unaccompanied by a change of state. A pure metal in cooling from its molten condition to a solid state will produce changes similar to Fig. 1b. The approach 1-2 to the horizontal portion represents the loss of sensible heat of the liquid and the curve from 3-4 represents a similar heat loss of the solid. The isothermal arrest (shown on the curve from 2-3) is caused by the heat evolution of the freezing metal giving up its latent heat of fusion. This cooling curve is typical of not only pure metals but also stable compounds and certain other alloys discussed later.

Fig. 1c and 1d represent simple binary alloys, the former showing the cooling of a solid solution (an alloy in which metals remain dissolved in each other when solid) in freezing from its melt and the latter an alloy where crystals of some primary phase solidify first followed by the simultaneous freezing of two phases from the melt along the horizontal portion 3-4. It will be noted that the solid solution did not cause the temperature to remain constant during its formation but rather that the change of liquid to solid took place over a range of temperature. This distinction clearly separates this group from the pure metals or compounds of Fig. 1b and also from the more insoluble metals shown in Fig. 1d. In Fig. 1d, for a binary system, when two solid phases form simultaneously from a melt as in a eutectic reaction (as seen later); cooling curves always manifest these horizontal portions.

Alloys which on solidification remain partially or completely soluble frequently show a decreased solubility of the constituent parts when allowed to cool to room temperatures. These further changes of state are usually accompanied by heat evolutions which will again affect the cooling curve, causing its smooth downward path to be disrupted by further arrests. When these heat reactions are small—and this is usually true of solid changes occurring at temperatures not far above room temperature—the change of direction in cooling curves escapes detection by ordinary means and other methods of inspection must be resorted to in order to reveal the complete story of the constitution diagram. These methods, approximately in their order of use, are: 1. Micrographic analysis; 2. X-ray diffraction; 3. dilatometric measurements; and 4. miscellaneous.

Classification of Systems—An inspection of the equilibrium diagrams given in this Handbook reveals that the changes taking place are often varied and complex. For example, alloys of copper and zinc or iron and carbon may exist when solid as a number of solid solutions or intermetallic compounds, and these states are not usually formed directly from the melt but follow after a series of intermediate steps or changes. In order therefore that these complex combinations may be clearly understood it is necessary to break them down into simple types which can be easily analyzed.

The usual method of classifying these simple binary types follows:

1. Alloys soluble in the molten state:
 - a. Soluble when solid
 - b. Insoluble when solid
 - c. Partially soluble when solid

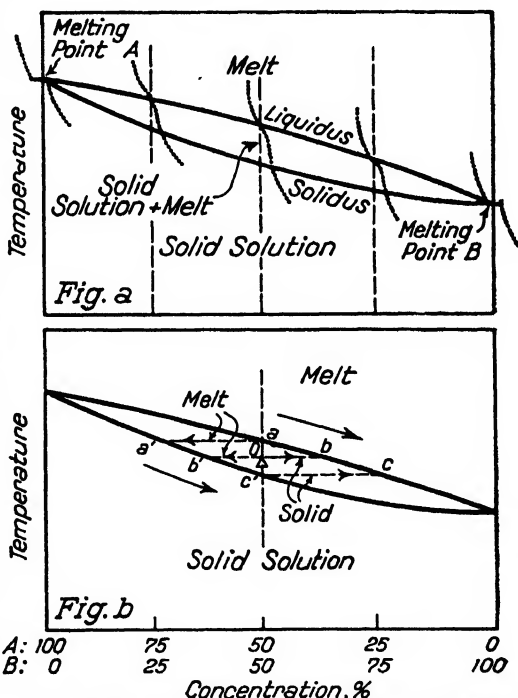


Fig. 2a—Illustration of two metals that form a solid solution.

Fig. 2b—Solidification of a solid solution alloy.

2. Alloys partially soluble in the molten state:
 - a. Insoluble when solid
 - b. Partially soluble when solid
3. Changes in solid alloys which are partially or wholly soluble on solidification.

Solid Solution Alloys—When two metals combine in this form the resulting alloy diagram may assume, as one possibility, a shape similar to Fig. 2a. The upper line connecting the initial freezing points of the several alloys slopes away gradually from the higher melting point metal A to metal B and is called the "liquidus" line since everything above it is in a liquid or molten condition. The lower line completing the envelope connects the end points of the freezing process and is known as the "solidus" line. Below it the alloys are completely solid.

In order that the mechanism of crystallization may be more clearly understood, it is desirable at this point to introduce several of the simple rules which outline the behavior of alloys during solidification.

Rule I, Qualitative Equilibrium—At any temperature in a heterogeneous field (containing either solid and melt or two different solid phases) the nature of the phases in equilibrium at some temperature can be determined by the intersections of the temperature horizontal with the conjugate boundaries to the field.

In Fig. 2a the conjugate boundaries to the solid and melt field are obviously the "solidus" and "liquidus" lines. Fig. 2b shows that for 50% alloy at temperature a the first solid solution crystals to form will be rich in metal A and have a composition of a' while the melt from which they crystallize has the original composition a. As the cooling progresses the average concentration of the solid and melt correspond to points b' and b respectively. This must follow since the initial solid solution, being rich in metal A, will deprive the residual melt of this metal thus increasing its B concentration and forcing it in the direction indicated. The end point of the freezing cycle will occur at temperature c' and here it is noted that the average composition of the solid is the same as the original melt (50% A, 50% B) while the last traces of melt in equilibrium with this solid have a composition of c.

Rule II, Quantitative Analysis—The amounts of the two phases in equilibrium at any temperature in a heterogeneous field may be determined by the well known "lever principle" of mechanics applied here as follows:

Assume that the intersection of the alloy composition line with the desired temperature horizontal acts as a fulcrum, the quantities of the two phases are then inversely proportional to the intercepts thus created on this temperature horizontal which extends to the conjugate boundaries of the field. In explanation of this refer to the 50% A alloy of Fig. 2b and suppose the temperature to be that at a, where freezing is about to begin. At this point the fulcrum is at a, there being no intercept to the right we have as yet no solid but all melt and 100% of the temperature horizontal lies to the left of the fulcrum. When cooling has progressed to temperature b, the fulcrum is at point o, and the amount of solid present is proportional to intercept o.b to the right of the concentration vertical while the quantity of remaining melt is proportional to the intercept ob' to the left of this vertical line. The entire length of the temperature line represents 100% of the alloy present. In a similar manner at temperature c the last melt has disappeared, and the whole intercept is to the right of the fulcrum, indicating that the alloy has now solidified completely.

The Phase Rule—Willard Gibbs in the latter part of the nineteenth century developed a relationship between the number of phases, the components and the degrees of freedom of a system, which has proven extremely useful as a guide in constructing alloy diagrams. This rule based on thermodynamic concepts and applied to metals in equilibrium may be stated mathematically as follows:

$$F = C + 1 - P$$

where

F = degrees of freedom

C = number of components

P = number of phases

Degrees of Freedom—The number of independent variables (either temperature or concentration of the phases) which may be altered without causing the disappearance of any phase, or the formation of a new phase.

Components—In alloy systems these are obviously the metals or their compounds and, for a given system, there should be chosen as components the smallest number of independently variable constituents by means of which the composition of each phase can be expressed.

Phases—Homogeneous, physically distinct matter, such as the physical states

liquid or solid with the latter having several possible forms, namely, pure metals, compounds and solid solutions.

As an illustration of the application of this rule, consider the crystallization of the 50% A alloy previously discussed. When the mass is at a temperature above the liquidus line the alloy is a homogeneous melt of A and B, resulting in but one phase in this two-component system (metal A and metal B). Inserting these values in the phase rule, ($F = 2 + 1 - 1 = 2$), the system has two degrees of freedom which implies that both temperature and concentration may be varied within limits without destroying or changing the equilibrium of the system. Another interpretation of this result is that the degrees of freedom also represent the number of variable factors which must be arbitrarily set before the state of the alloy can be determined. When both temperature and concentration vary the system is said to be *bivariant*.

On cooling this alloy to temperature *b*, Fig. 2b, two phases are present, one solid *b'* and one melt at *b*. The system is then *monovariant* (1 degree of freedom) since $F = 2 + 1 - 2 = 1$. If now either the temperature or the concentration of only one of the phases be set, the remaining variable factors immediately follow and the condition of equilibrium is completely determined. Hence in such a binary system it is possible to have two phases such as solid and melt present over a range of temperature and freezing need not occur isothermally as in pure metals.

To make this clear suppose the phase rule be applied to a pure metal while freezing. Obviously two phases are present (solid and melt) and this system is of one component. The degrees of freedom are now represented by $F = 1 + 1 - 2 = 0$ and the system is said to be *invariant*. From this it follows that the temperature must remain constant so long as the solid and melt co-exist and this phenomenon is of course well known to all.

Thus far it has been shown that when solidification occurs in the solid solution type alloys Fig. 2a the concentration of the first particles of solid will be considerably richer in metal A than the melt and also the last melt will be correspondingly richer in metal B. This produces solid crystals which are partially heterogeneous in that the nuclei are rich in one metal whereas the outer surfaces which formed last are rich in the other metal. On slow cooling from the "solidus" line, diffusion or equalization takes place and—given sufficient time at elevated temperature—will be complete at room temperature. The structure will then appear microscopically as a single phase, similar to a pure metal. The alloys of copper-nickel or gold-silver are completely soluble both in the liquid and solid states and the resulting constitution diagrams are similar to the type just discussed (see pages 1353 and 1503).

In addition to the type just described, two other alloy diagrams, showing complete solubility (miscibility) in the solid state, are possible. The first of these, in which the "liquidus" and "solidus" are both depressed, is shown in Fig. 3a and at the minimum temperature these lines become tangent. The cooling curve at this point is similar to that of a pure metal. In other respects the path of crystallization of alloys in this series will follow through precisely the same steps as that of the type just discussed.

Fig. 3b shows a type of solid solubility resulting from a maximum tangent point of both "liquidus" and "solidus" lines. No important binary metal groups are known to follow this behavior but there are several nonmetallic combinations that do. Of the more complex binary systems such as copper-aluminum (page 1342) it will be noted that in the formation of the beta solid solution a maximum occurs at 1047°C. while the system of copper and beryllium (page 1344) contains a minimum temperature in the field of precipitation of its beta solid solution.

Alloys Soluble in the Melt but Insoluble when Solid—These alloys can be divided into three subgroups: (a) Simple eutectic; (b) simple eutectic and stable intermetallic compound; (c) peritectic types.

(a) *Simple Eutectic*—When two metals are insoluble in each other in the solid state, the addition of one to the other will usually cause the freezing temperature of the melt to be lowered (Fig. 4). The intersection of the "liquidus" lines *ae* and *de* at *e* produces an alloy of the lowest freezing point in the series and is called the *eutectic* of the system. The location of this eutectic is specific for a definite combination of metals but may be located anywhere from pure A to pure B throughout the various alloys. A practical example of this alloy diagram is the zinc-tin system (page 1756).

Path of Crystallization—Alloy I (Fig. 4) rich in A will on cooling from a temperature of *x* lose sensible heat until temperature *y* is reached. At this point the first particle of solid appears and by the insertion of the temperature horizontal.

Rule I, this solid is found to be pure A. Fig. 4 shows that the boundaries to the heterogeneous field of solid A plus melt are the solidus line *ab* and the liquidus line *ae*.

A break in the smooth path of the cooling curve will be noticed due to the evolution of heat by the solid A being formed. It follows now that if pure A separates from the melt, this melt becomes increasingly richer in B and with falling temperature, its concentration will vary from its initial condition *y* along the liq-

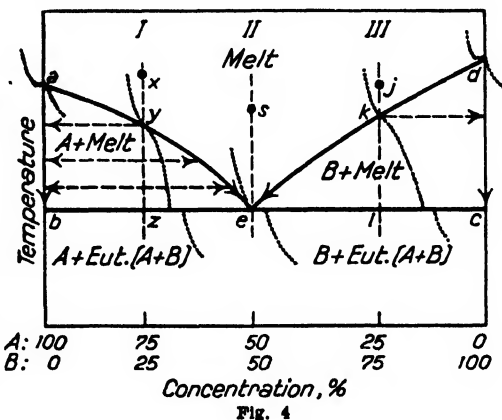
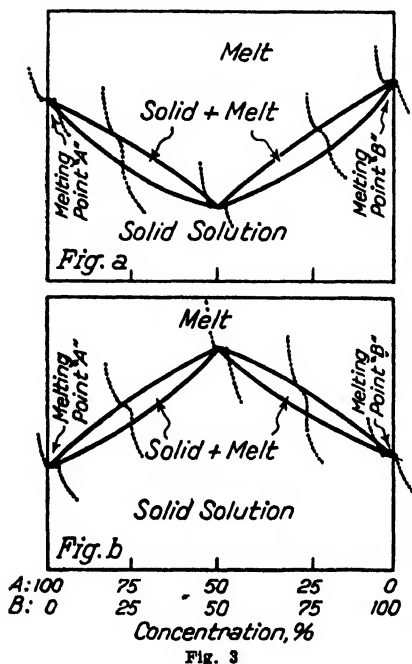


Fig. 3a—Alloy diagram showing complete miscibility in the solid state with the liquidus and solidus depressed.

Fig. 3b—Type of solid solubility resulting from a maximum tangent point of both the liquidus and solidus lines.

Fig. 4—Diagram for two metals that are insoluble in each other in the solid state.

uidus line *ae* until the eutectic point *e* is reached. Meanwhile the solid A crystals have grown in size and number and at the eutectic temperature *bze* equilibrium is established between primary A crystals just formed and a melt whose concentration is *e*. The melt now freezes, depositing simultaneously the remaining A and B as separate and distinct phases. The temperature remains constant while eutectic melt is present. The resulting eutectic microstructure usually shows finely divided alternate lamellae of A and B. Applying the phase rule to this part of the system we find present three phases, two solids, pure A and pure B, and the eutectic melt *e*. In this binary system the eutectic freezing is therefore an invariant condition since $F = 2 + 1 - 3 = 0$. This simply means that whenever both solid A and B are present with the melt *e* the temperature must remain constant and that only one certain temperature will satisfy. This accounts for the horizontal "solidus" *bec* or base to the "liquidus" curves *aed*. The microstructure of the completely solidified alloy I will consist of primary A crystals in a matrix of eutectic (A + B).

Alloy II—For an alloy whose concentration is that of the eutectic *e* the cooling of the melt will occur from *s* to *e* without the formation of any solid. At the eutectic temperature *bec* the solidification of pure A and pure B again takes place simultaneously at constant temperature. The resulting solid microstructure will be entirely eutectic (usually a finely divided matrix of A and B).

Alloy III—When the alloy has a composition between *e* and *c* it will on cooling below the liquidus line (*d e*) precipitate primary B crystals thus forcing the composition of the remaining melt to the left. This process continues to the eutectic temperature *elc* where the formation of the solid eutectic (A + B) occurs. The final microstructure will consist of primary B crystals imbedded in a matrix of eutectic (A + B).

(b) *Eutectic Alloys with Stable Intermetallic Compound*—Many binary alloys contain one or more intermetallic compounds but are otherwise completely insoluble when solid. Fig. 5 is typical of this series, containing one compound A_xB_y and two separate eutectics at e_1 and e_2 . The cooling of the intermetallic compound A_xB_y is similar to a pure metal and its melting point is at a maximum point c in the liquidus line e_1ce_2 . The simplest method of analyzing these alloys is to break down the composite diagram into simple eutectic types as shown to the left and right of the principal figure. It can then be assumed that A_xB_y is a separate component and the two binary figures are subject to the same changes previously described for eutectic types.

Briefly, alloys whose composition fall between b and e_1 , have an excess of A over and above the eutectic e_1 . The resulting solid will contain primary A in a ground mass of eutectic e_1 ($A + A_xB_y$). To the right of this eutectic, the compound will precipitate out first and the final microstructure will contain it as a primary phase surrounded also by eutectic e_1 . Compositions to the right of the A_xB_y vertical will yield structures as indicated in the diagram with a matrix or background of eutectic e_2 ($A_xB_y + B$).

(c) *Peritectic Systems*—When a binary compound is unstable with a melt of its own composition the resulting diagram takes on a new form as in Fig. 6. The figure itself will, in part, explain the reason for the many headings under which this system is discussed by the profession. In addition to the title given, it is variously labeled "transition type," "unstable compound" and "hidden maximum," all of which tend to be descriptive of the unusual change occurring at the temperature bce' .

An alloy of composition I will on cooling to temperature t remain in a soluble molten state. At this temperature nuclei of solid A come into equilibrium with the melt, thus forcing it to the right toward point e' (peritectic point) as cooling proceeds, the precipitation of solid A continues. At the peritectic temperature bce' the equilibrium in the alloy is between a predominant amount of solid A and the remaining melt whose composition is e' . It is at this point that the unstable compound A_xB_y enters the picture as the third phase, creating an invariant condition, with the resultant temperature arrest in the cooling curve. Obviously the compound A_xB_y cannot wholly form from a melt whose composition lies to the right at e' and is therefore much richer in metal B . To compensate for this, some of the metal A reacts with the melt, as the compound forms, maintaining its concentration at e' until its disappearance. The final microstructure of the mass must be solid A crystals formed prior to the transition surrounded by the compound A_xB_y .

For alloy II , the initial reaction will be like that of alloy I . Cooling from temperature m to n will permit the freezing of primary A but to a much lesser extent than before. At the transition temperature the equilibrium will again be between solid A , melt e' and the compound A_xB_y . The reaction continues as before with the resorption of primary A into the melt while A_xB_y freezes out, but not for long, since the quantity of excess A is not large and it soon vanishes completely. With the disappearance of the solid A phase the temperature no longer remains constant and the concentration of the melt gradually slides toward the eutectic e while the A rich intermetallic compound A_xB_y forms. Freezing ends at the eutectic temperature def

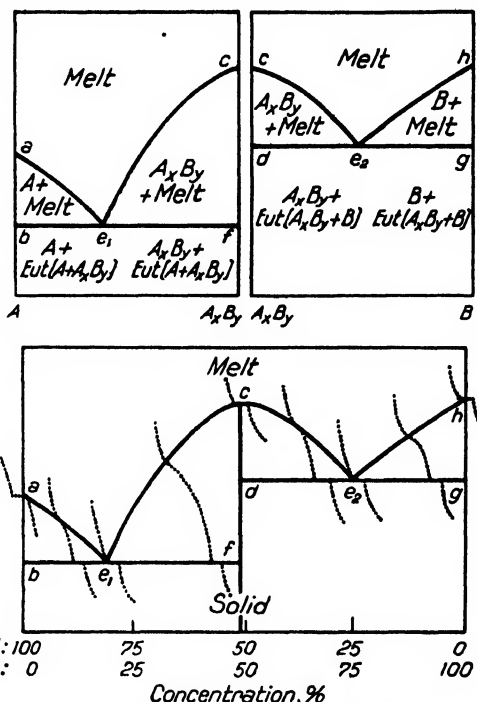


Fig. 5—Typical diagram of binary alloys containing one or more intermetallic compounds and are insoluble when solid.

when the small amount of residual melt simultaneously precipitates A_xB_y and B in a typical eutectic arrangement.

When the composition of the melt is exactly that of the compound A_xB_y , the two phases primary A and melt e' are correctly proportioned and disappear simultaneously at the transition temperature.

Alloys Soluble in the Melt but Partially Soluble when Solid—Most alloy systems of commercial importance fall in this group although frequently the degree of solid solubility is only slight. Solid solutions are customarily labeled with letters of the Greek alphabet to distinguish them from pure metals and compounds (see page 67 for Greek alphabet). The number of possible fundamental types of diagrams is about the same here as it was in the previous series and their analysis will follow the same order.

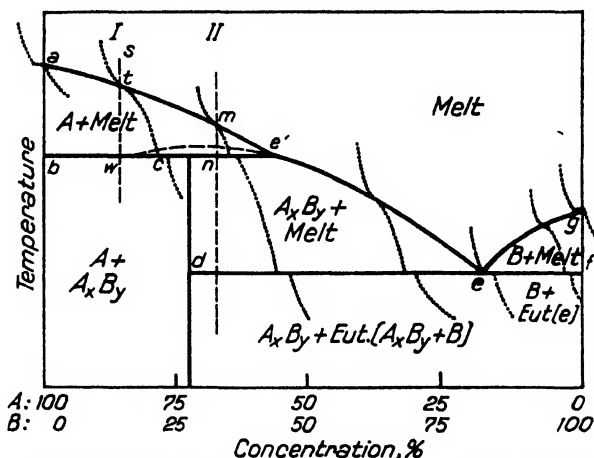


Fig. 6—Diagram of binary compound unstable with a melt of its own composition.

Simple Eutectic—An alloy rich in metal A and having a composition similar to I in Fig. 7 will on freezing first deposit as nuclei, solid solution crystals whose composition tends to be almost pure A. As these crystal centers grow in size by the further deposition of solid metal, the concentration of the mass becomes increasingly richer in metal B. The liquid concentration follows along the heavy portion of the liquidus line ae while the average solid concentration is indicated by the heavy portion of the solidus line ab . Solidification is complete at the temperature corresponding to the intersection of the concentration vertical with the solidus line ab and no further change occurs in cooling to room temperature. It is evident that the portions of the diagram to the left of b or to the right of c trace the same path of crystallization

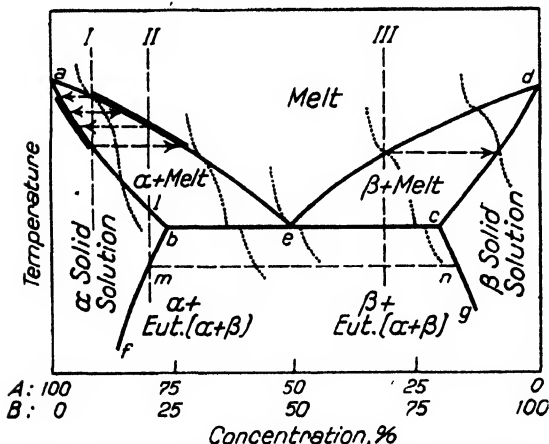


Fig. 7—Diagram of simple eutectic showing the freezing of solid solution crystals whose composition is rich in one of the metals.

as the solid solution systems discussed in the beginning.

There is this difference, however, the A rich solid solution α is saturated with metal B when the composition of the alloy is b and in a like manner the B rich solid solution β becomes saturated with metal A when the amount of this phase corresponds to composition c . The predominant metal in either case is considered to be the solvent and when the compositions tend to approach the 100% A or B verticals the solid solutions thus formed are termed unsaturated. These unsaturated solid solutions may of course become saturated at lower temperatures and precipitation of the second phase then occurs. For example, alloy II which is unsaturated with respect to metal B will, after solidification (at I), cool as a homogeneous solid solution to a temperature m (at the intersection of the concentration vertical with

the solid solubility line bf) where a second solid phase precipitates from this homogeneous α . The nature of this phase can be determined by applying Rule I—drawing the temperature horizontal at m it is found to intersect the solid solubility line cg on the right and β solid solution of n concentration is the precipitate phase.

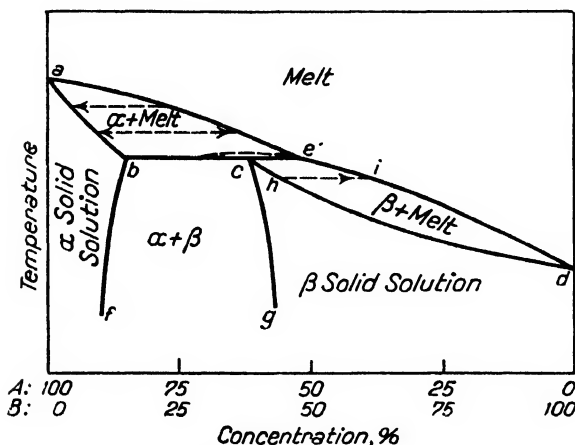


Fig. 8—Diagram of peritectic type.

sect the solid solubility line cg and from which the α phase will separate. For the portion of the diagram lying between compositions b and c the reaction is of a typical eutectic form. Alloy III for example will contain primary crystals of β surrounded by a lacy network matrix of eutectic structure. There are many simple actual alloy systems on this order such as $Sb-Pb$, $Sn-Pb$, $Bi-Pb$, $Cu-Ag$, and others.

Peritectic Type—Comparing this type diagram, Fig. 8, with the previous peritectic equilibrium for insoluble conditions (Fig. 6), it is clear that the melt traces precisely the same path in both instances and the only distinction occurs in the solid phases which are now the two solid solutions α and β as compared with pure A and the compound A_2B in the former case.

Commercially common alloys which behave in a fashion comparable to simple alloys already considered are not difficult to find. There are peculiar combinations of several simple systems or perhaps a repetition of the same. A case in point is the tin-antimony constitution diagram on page 1699.

Partial Solubility of the Melt with Insoluble Solid—When two metals are partially soluble in the molten state the liquidus line of the equilibrium diagram now has superimposed on it the heterogeneous two melt field as shown in Fig. 9. The alloy system chosen to illustrate this type of reaction is of a simple insoluble eutectic

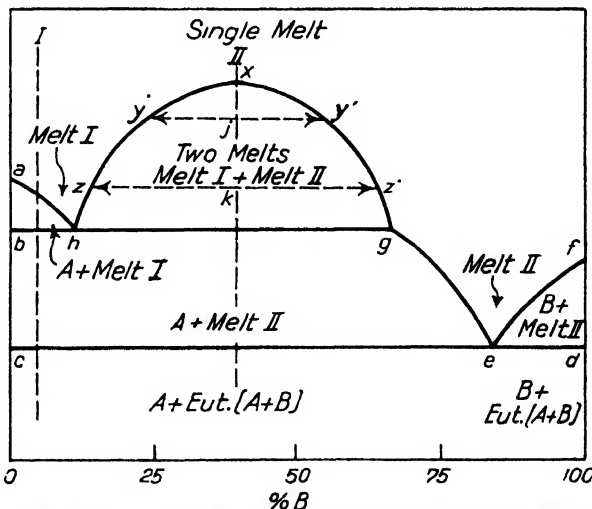


Fig. 9—Diagram of partial solubility of the melt with insoluble solid.

type. An inspection of the final phases and microstructures indicates that the breakdown of the single melt into two melts does not affect the final result. Alloy I will on cooling through the liquidus line *ah* freeze out primary A crystals to the

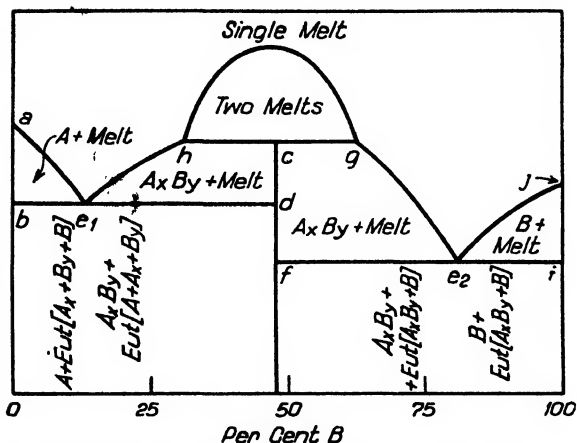


Fig. 10—Variation of partial solubility of the melt with insoluble solids.

temperature *bhg*. On arriving at this temperature the melt will have a composition of *h* and continued precipitation of solid A from this melt will cause the formation of the second melt of composition *g*. This may be stated in equation form as follows:



This three phase reaction, sometimes referred to as a "monotectic" reaction, takes place isothermally and further drop in temperature does not occur until the melt *h* disappears. The solidification process then is the same as for the simple eutectic type in that primary A continues to form, forcing the melt ultimately to the eutectic concentration *e*.

Solidification of alloy II differs from alloy I only in its initial stages. Cooling below temperature *x* above the two melt field, the single melt separates into con-

jugate melts which at temperature *j* will be of composition *y* and *y'* and at *k*, *z* and *z'* respectively. At temperature *bhg* the two melts will have the compositions of *h* and *g*. The cooling reactions from this point are now the same as before with melt *h* precipitating some solid A.

The dome shaped field limiting the temperature and concentrations at which two melts may exist is not always well defined in its upper regions. This is due to the small thermal changes which occur in the formation of the conjugate melts. The isothermal reaction is, however, always clearly defined. Copper and lead (page 1349) or zinc and lead (page 1748) both show partial solubility in the molten state.

Another variation of this type of equilibrium, where the melt is partially soluble, is illustrated in Fig. 10. The dome shaped two melt field is now superposed directly over an intermetallic compound. Alloys of this system having a composition between *h* and *c* will on cooling to a temperature of *hcg* consist of melt *h* and melt *g* with an excess of the former. The compound A_xB_y , then freezes isothermally from a combination of the two melts and the reaction is complete when melt *g* disappears.

For alloys having a composition between *c* and *g* the reactions are the same except that melt *h*, which is now present to a lesser extent, will disappear first, following which the compound A_xB_y continues to freeze in the usual manner. The three phase isothermal reaction at temperature *hcg* is sometimes termed a "syntectic" reaction and the diagram is named accordingly.

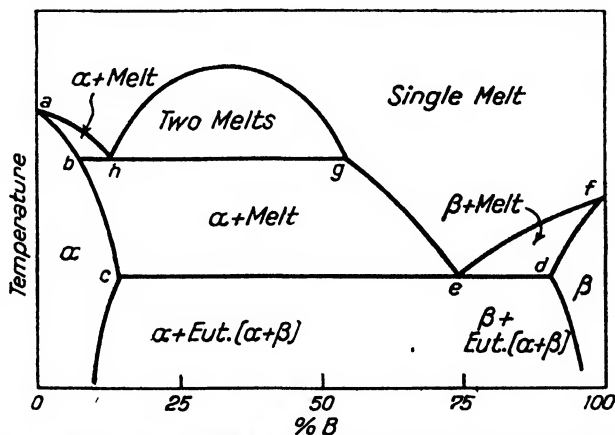


Fig. 11—Diagram for an alloy partially soluble in both the liquid and solid states.

Partially Soluble in Both Liquid and Solid States—By slightly modifying the diagram of Fig. 9 as in Fig. 11 partial solubility in the solid state is indicated. If in the above analysis the A rich solid solution α is substituted for the metal A and the B rich solid solution β for the metal B we can trace through precisely the same steps as before. The system of tin and phosphorus (page 1705) is of this type.

In a similar manner the alloy system of Fig. 10 may be altered by having not only primary solid solutions α and β at the terminal points but also by replacing the intermetallic compound A_2B_3 by an intermediate phase showing extended solubility. This intermediate phase or solid solution which could be labeled γ will then result from the combination of the two melts b and g and replaces A_2B_3 on the diagram.

Complete Insolubility in Both Liquid and Solid States—The last of the liquid-solid transitions, sometimes presented, is that of a binary system which is insoluble under all conditions. The two metals act independently of each other and solidify at their respective freezing points regardless of composition. The diagram (Fig. 12) consists of two parallel horizontal lines and the resultant mass likewise consists of two distinct layers. Fe-Ag resembles this type.

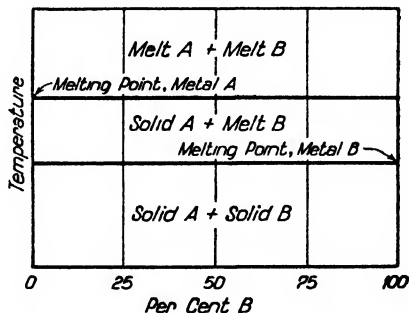


Fig. 12—Diagram showing insolubility in both the liquid and solid states.

Transformations in the Solid State—

The discussion just completed treats entirely with the transformation of liquids or melts into solids. The study of the decomposition of solid alloys, which exist in the form of solid solutions on freezing is of equal importance. These solid solutions may transform into compounds, secondary solid solutions, or the simple metals much in the same fashion as the reactions previously described and it is the control of the rate of these decompositions which makes it possible to vary the ultimate physical properties of alloys.

The first factor of importance in the study of solids deals with the change which some pure metals undergo on cooling, known as *polymorphism* and defined as that property of a metal which causes it to appear in more than one solid crystalline form. These various forms of a metal are labeled with letters of the Greek alphabet (like solid solutions) and may be distinguished not only by the arrangement of the atoms in their crystal lattices but also by the difference in some of the physical properties in each instance. For example pure iron appears on freezing as delta, later as gamma and finally at ordinary temperature as alpha iron.

Outwardly, the polymorphic modifications of iron appear much the same but with some substances this property too may vary greatly as in the case of carbon which may exist as a diamond, graphite or temper carbon. Likewise ordinary white tin on cooling to subzero temperatures may be converted to a gray, powdery state.

Complete Solid Solutions of Two Polymorphic Metals—Certain binary combinations of metals which are miscible when solid will, because of polymorphic modification of one or both constituents, cause secondary changes indicated by Fig. 13a, b, c.

The first of these, Fig. 13a, may be produced by two metals A and B when each exists in two polymorphic states, α and β , and also when because of the similarity of the two metals in crystalline form, and atomic radius, they tend to remain in solution as a solid. The essence of the second transformation from α to β solid solution is the same as that of the liquid to solid change occurring above it. The α solid solution will on cooling remain homogeneous until the upper transformation or upper critical line acb is reached. At this temperature are born the first crystals of the β solid solution whose concentration can be obtained by drawing temperature horizontals in the $\alpha + \beta$ field and the transformation from α to β continues until the lower critical adb is reached. The change is now complete and further cooling to room temperature will leave this β phase in a homogeneous state.

Loop Type Diagrams—The envelope abcd enclosing the $\alpha + \beta$ field is commonly called a loop. In both Fig. 13a and 13b this loop is closed whereas in the third type 13c it remains open. The latter two result when a metal such as B goes through no polymorphic changes, though it is possible that in Fig. 13c the $\alpha + \beta$

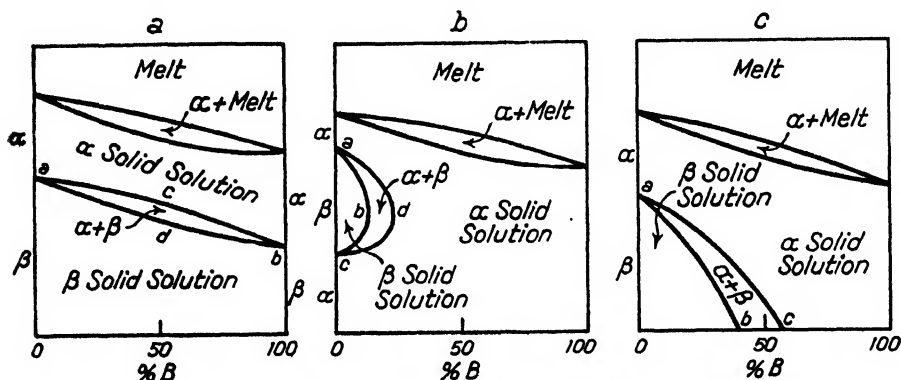


Fig. 13a, b, and c—Typical diagrams for complete solid solutions of two polymorphic metals.

field may be closed at extremely low temperatures where a second modification of either A or B may exist.

The alloys of iron-tungsten or iron-chromium among others exhibit a characteristic closed loop similar to Fig. 13b where the γ form of iron dissolves either tungsten or chromium to a limited extent. In this instance it is possible for an alloy whose composition lies in this range to change, on cooling, from the α solid solution to the second type and later back to the α form. It is also possible, when cooling drastically from within the loop, to maintain the intermediate state. Of the third type, Fig. 13c, iron and nickel offer a good example and it is possible to obtain at ordinary temperatures either the α form, a mixture of α and β (β in Fig. 13c but γ in the Fe-Ni system) or the β form alone. The mechanism of the change is similar in each case.

Order-Disorder—Another type of transformation in the solid state is the so-called order-disorder change which is described in the article on the Crystal Structure of Metals and Alloys in this Handbook.

Solid Solution Decomposition Resulting in Partial Solubility—When solid solutions become less soluble they may also go through a eutectic-like reaction in the solid state producing ultimately partially or wholly insoluble aggregates.

The partially soluble state is illustrated by Fig. 14a and the eutectic type of reaction, now called *eutectoid* occurs at the temperature *bec*. The path of crystallization for an alloy to the left of the eutectoid *e* and between *b* and *e* can be traced as follows:

The primary solid solution γ on cooling through the transition *ae* at *m* will precipitate the secondary solid solution α having a composition *n*. This α phase, commonly called the proeutectoid constituent, will have a composition varying to *b* at the eutectoid temperature *bec*. Meanwhile the γ solid solution will become richer in metal B and at this temperature its concentration is that of point *e*. A simultaneous deposition of the two phases α_e and β_e solid solutions from the residual γ_e then produces the characteristically finely divided matrix of a eutectoid reaction. The microstructure of the "eutectoid" is usually that of alternate lamella of α and β or

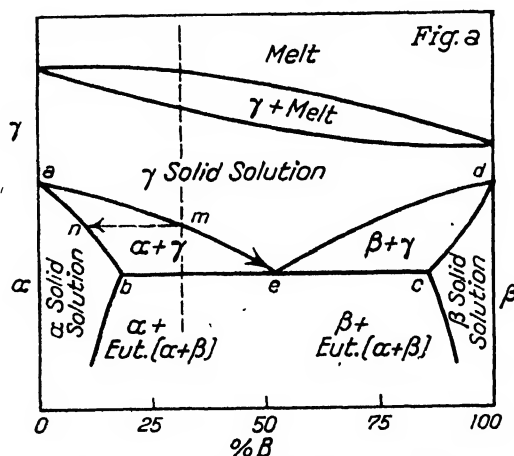


Fig. 14a—Diagram for solid solution decomposition resulting in partial solubility.

spheroids of one in the other, requiring rather high magnification to bring about their resolution. Its particle size is much smaller than that of corresponding eutectic structures.

A composition exactly at *e* will, of course, result entirely in a eutectoid structure while alloys to the right between *e* and *c* will be made up of proeutectoid β imbedded in the eutectoid background.

Decomposition of Solid Solutions Resulting in Insolubility—When the solid solution breaks down into complete insolubility and is of the eutectoid type its form may be depicted by Fig. 14b. In this case the proeutectoid constituent is either pure A or pure B while the eutectoid contains both. The transformation is similar to the previous type.

Decomposition of Solid Solutions Resulting in a Peritectoid Reaction—The last class of solid solution decomposition is that of the peritectic or resorption type and is called peritectoid or metaectectic. This form of equilibrium, and this is equally true of all of the diagrams previously given, may have many variations. Fig. 15a, b, c show three types of diagrams. The mechanism of the transformations of solid alloys of this type is similar to the liquid-solid reactions of systems having the same form of equilibrium diagram. Thus Fig. 15b shows how the β solid solution like the melt of Fig. 6 becomes ultimately

completely insoluble and consists for alloy I of a mixture of A and the compound A_2B_3 (the product of the resorption of primary A with the β phase) while alloy II carries on below this transition temperature and does not break down completely until the eutectoid temperature *def* is reached. The end microstructure for this alloy, as indicated in the figure, will be made up of excess compound A_2B_3 imbedded in a matrix of eutectoid ($A_2B_3 + B$).

The only purpose in presenting Fig. 15c is to show how frequently the dotted solid solubility lines *cm* and *dn* shift to one side and become joined as at the point *b* where in some instances a polymorphic phase change occurs. This is particularly true of the alloys of iron in the high temperature field and for compositions rich in iron. The phases are labeled as in the iron-carbon system. The δ solid solution on cooling through the upper transformation line *cb* will decompose to the γ solid solution and the transition is complete at the lower transformation line *bd*. Between these two conjugate boundaries δ and γ co-exist.

Summary—Summarizing the previous discussion on the constitution diagrams of binary systems, certain simple rules may be stated which should facilitate the reading of these graphic illustrations of metallic equilibrium.

1. Under inclined liquidus lines two phases exist, one of which is the melt.
2. Under inclined upper solid transformations two solid phases exist one of which is a solid solution.
3. Under inclined "solidus" lines or inclined lower solid transformations a single solid phase exists (solid solution).
4. Along horizontal lines three phases exist.
5. Two of these phases are indicated by the compositions at the ends of the horizontal line.
6. The third phase depends on the shape and nomenclature of the diagram as shown in Fig. 16.
7. Stable intermetallic compounds usually occur under maximums of the liquidus lines and appear as a vertical or vertical range extending from the liquidus down to room temperature.
8. The drawing of temperature horizontals in heterogeneous (two phase) fields yields the compositions of the phases in equilibrium at that temperature.
9. The reactions which take place on cooling will also occur on heating but in a reversed order and for solid transformations at slightly higher temperatures.

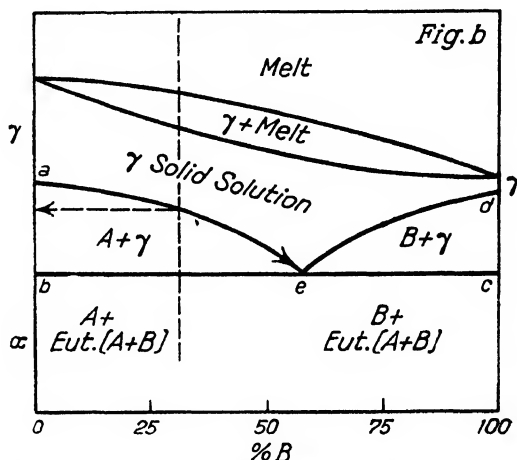
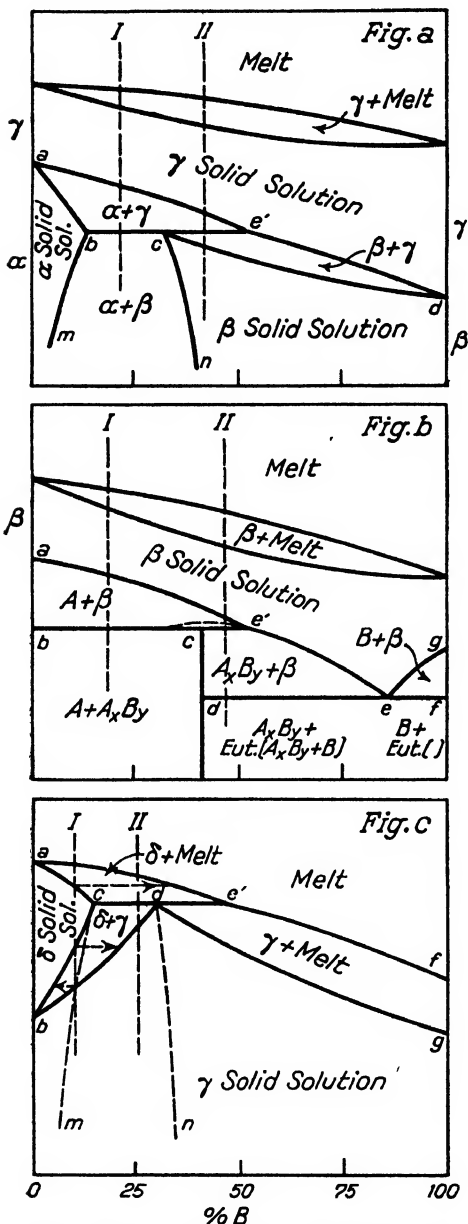


Fig. 14b—Diagram for decomposition of solid solutions resulting in insolubility.



10. Slow cooling is essential if normal equilibrium reactions are to occur.

11. Rapid cooling tends to preserve the state of the alloy in its initial condition which existed immediately prior to cooling.

12. Intermediate rates of cooling may produce unusual final aggregates due to the particle size of the precipitated phase and the obstructive effect caused thereby.

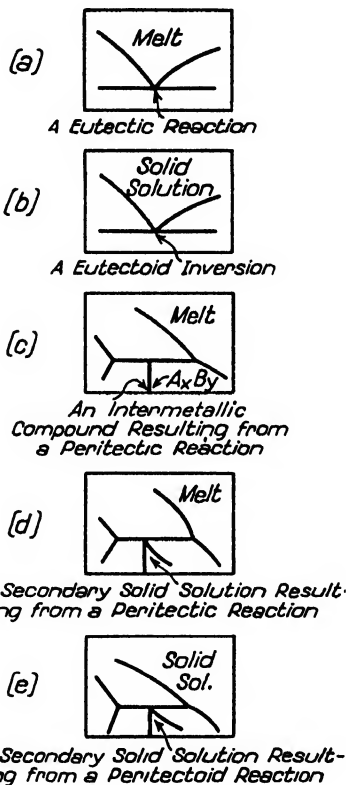


Fig. 16—Shape and nomenclature of phases in the constitution diagram.

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Constitution of Binary Alloys of Iron and Certain Other Elements

By R. M. Parke*

Of the various binary systems containing the element iron as one component, work on about 55 has been reported in the literature, while 30 have been investigated sufficiently to permit the construction of at least a partial equilibrium diagram. Several systems of the latter group have been separately treated in other sections of this handbook. The present article summarizes the more important information that exists for some 39 of the rarer iron binary systems. For a more complete presentation of the available information on these systems, the reader is referred especially to the excellent works of Hansen ("Der Aufbau der Zweistofflegierungen" published by Julius Springer, Berlin, 1936), Jänecke ("Kurzgefasstes Handbuch aller Legierungen", published by Otto Spamer, Leipzig, 1937) and Vogel ("Handbuch der Metall Physik, II—Die heterogenen Gleichgewichte" edited by G. Masing, published by Akademische Verlagsgesellschaft, Leipzig, 1937), each of which was extensively consulted here.

Antimony-Iron—Antimony-iron alloys have been studied by Laborde¹ and Maey², by Kurnakow and Konstantinow³, Wever⁴, Hagg⁵, and Vogel and Dannöhl⁶. From these researches it appears that the Sb-Fe system has a closed gamma field, two compounds⁷ occur (Fe₃Sb, FeSb₂), and the iron-rich solid solution⁸ will hold up to 7%† Sb. The limit of the gamma loop has been tentatively estimated by Vogel and Dannöhl⁶ at slightly over 2% Sb.

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- ⁶R. Vogel und W. Dannöhl, Die Zweistoffsysteme Eisen-Kupfer und Eisen-Antimon, Arch. Eisenhüttenw., 1934-35, v. 8, p. 39.

Argon-Iron—Argon¹ and helium do not diffuse through iron so that it may be assumed that these gases are not soluble in iron. According to Sieverts and Bergner² electrolytic iron does not absorb any inert gas at 1200°, 1400°, or 1500°C.

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Arsenic-Iron—The constitution of As-Fe alloys has been studied by Friedrich¹, Oberhoffer and Gallaschik², Weyer³ and Hagg⁴. The eutectic occurs at about 70% Fe and 830°C. between the compound Fe₃As and the iron-rich (92% Fe) solid solution. From Hagg's work it appears that the solubility of As in Fe decreases with decreasing temperature. Wever determined that a closed gamma field exists. An additional compound (FeAs) was identified by Hagg.

Hansen⁵ has presented a partial diagram based on the work of the above investigators and others. This diagram places the limit of the gamma loop provisionally at about 1.5% As since the existence of the gamma loop is not in agreement with the work of Oberhoffer and Gallaschik².

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Prepared for the Subcommittee on Alloying Elements.

The membership of the subcommittee was as follows: Jerome Strauss, chairman; Walter Crafts, J. W. Sands, Harry Knowlton, L. L. Farrell, A. J. Herzig, Emil Janitzky, C. H. Herty, Jr. and E. C. Bain.

†Unless otherwise stated compositions are given in weight per cent.

Barium-Iron—Barium, lithium, sodium, potassium, rubidium, caesium, magnesium, calcium and strontium¹ are insoluble in solid iron. Iron is not dissolved by the foregoing liquid metals, and although their solubility in liquid iron is not known, (the boiling points of the metals are all below the melting point of iron) the possibility of the formation of alloys is considered improbable.

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Beryllium-Iron—The liquidus and solidus lines of the iron side of the Fe-Be diagram have been determined by Oesterheld¹. He estimated that iron could dissolve at least 6.5% Be at 1155°C., the eutectic temperature. The eutectic contained 9% Be. Oesterheld believed that the solubility of Be in Fe decreased with temperature and this is supported by precipitation hardening experiments of Masing² and Kroll³. Oesterheld tentatively identified a compound of the formula Be_3Fe , which was confirmed by Misch⁴, who determined that Be_3Fe has a hexagonal lattice similar to MgZn_2 . Misch also investigated the compound Be_2Fe (55.32% Fe) which he stated has a Cu_2Mg structure similar to CuBe_2 .

Wever and Müller⁵ found that the Fe-Be system has a closed gamma loop and that the alpha-gamma transformation disappears at 0.45% Be.

Hansen⁶ and Jänecke⁷ published a partial equilibrium diagram (79-100% Fe).

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⁷E. Jänecke, *Kurzgefasstes Handbuch aller Legierungen*, Otto Spamer, Leipzig, 1937, p. 155

Bismuth-Iron—According to Isaac and Tammann¹, Bi and Fe are practically insoluble in each other in the molten state, and this has been confirmed by Hagg². Using a magnetic method Tammann and Oelsen³ determined that 2×10^{-4} to $4 \times 10^{-4}\%$ Fe was dissolved in Fe-Bi alloys heated at 400 and 1600°C. under a hydrogen atmosphere.

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³G. Tammann und W. Oelsen, Die Abhängigkeit der Konzentration Gesättigter Mischkristalle von der Temperatur, *Z. anorg. allgem. Chem.*, 1930, v. 186, p. 277, Die Löslichkeit des Eisens in Blei, Silber, Wismut und Cadmium.

Boron-Iron—This system has been studied by Tschischewski and Herdt¹, Hannesen², Vogel and Tammann³ and Wever and Müller⁴. On the basis of these researches Hansen⁵ has constructed a partial diagram. A eutectic between the gamma phase and the compound Fe_2B occurs at 3.8% B and 1174°C. The maximum solubility of B in alpha iron is 0.15% at 915°C., the solubility decreasing at lower temperatures. The maximum solubility of B in gamma iron is 0.10% at 915°C., while the maximum solubility in delta iron is 0.15% at 1381°C. Wever and Müller⁴,⁶ determined that the compound Fe_2B has a body-centered tetragonal lattice with 4 Fe_2B groups in the unit cell. Bjurström and Arnfelt⁷ verified the structure of Fe_2B and also determined that the monoboride FeB has a rhombic structure with 4 FeB groups to the unit cell. Wever and Müller⁴ concluded that B slightly raises the alpha-gamma transformation of iron.

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⁷T. Bjurström und H. Arnfeldt, Röntgenanalyse des Eisen-Bor-Systems, Z. physik. Chem. B, 1929, v. 4, p. 469.

Cadmium-Iron—Cadmium is insoluble in solid iron. Tammann and Oelsen¹ determined the solubility of iron in molten cadmium in the range 400-700°C. to be 3×10^{-4} to $2 \times 10^{-4}\%$ Fe. According to Daniels² a compound, Cd_3Fe , exists.

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Caesium-Iron—See barium-iron

Calcium-Iron—See barium-iron

Cerium-Iron—The Ce-Fe equilibrium diagram has been completely determined by Vogel¹. Two compounds, $CeFe_2$ and Ce_2Fe_3 , were identified. The eutectic occurs at 4.5% Fe and 640°C. The maximum solubility of Ce in gamma Fe is 15% Ce at 1090°C., while in alpha iron the maximum solubility is tentatively placed at 12% Ce. Ce slightly raises the temperature of the alpha-gamma transformation. The pyrophoric property of Fe-Ce alloys is greatest at 30% Fe according to Auer v. Welsbach², but see also Vogel¹ for an explanation of this property. See Hansen³ or Jänecke⁴ for the diagram of this system.

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⁵E. Jänecke, Kurzgefasstes Handbuch aller Legierungen, Otto Spamer, Leipzig, 1937, p. 167.

Cobalt-Iron—Iron and cobalt form a continuous series of solid solutions. Iron-cobalt alloys solidify over a very narrow temperature range (5-10°C.)¹, with a minimum of 1477°C. between 30% and 40% Fe. Cobalt raises the gamma-delta transformation of iron. This metal also raises the alpha-gamma transformation continuously up to about 45% Co (975°C.) when further additions lower the temperature of the transformation until at approximately 78% Co gamma iron is stable at room temperature. Iron drastically lowers the transformation of the hexagonal close packed epsilon cobalt phase to the face-centered cubic gamma phase.

Based on the work of Guertler and Tammann¹, Ruer and Kaneko², Kase³, Masumoto⁴, Grenet⁵, Kussmann, Scharnow and Schulze⁶, Andrews⁷, Ellis⁸, Osawa⁹ and others, Hansen¹⁰ and Jänecke¹¹ have constructed a complete equilibrium diagram of cobalt-iron alloys. Recently Andrew and Nicholson¹² confirmed the essential points of the diagram except that they believe that there is a wide alpha + gamma region extending from 74-82% cobalt.

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¹¹M. Hansen, Der Aufbau der Zweistofflegierungen, Julius Springer, Berlin, 1936, p. 487. (Kobalt-Eisen).

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Columbium-Iron—Bolton¹ reported that columbium and iron are mutually soluble in all proportions in the liquid state and Wever² determined that Cb closes the gamma iron region.

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²F. Wever, Ueber den Einfluss der Elemente auf den Polymorphismus des Eisens, Arch. Eisenhüttenw., 1928-29, v. 2, p. 739; Naturwiss. 1929 v. 17, p. 304.

Gallium-Iron—Kroll¹ states that gallium will alloy with iron.

Reference

¹W. Kroll, Legierungen des Galliums, Metallwirtschaft, 1932, v. 11, p. 435.

Germanium-Iron—Wever¹ believes that the Fe-Ge system has a closed gamma field.

Reference

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Gold-Iron—From the work of Isaac and Tammann¹, it has been determined that iron and gold are miscible in all proportions in the liquid state. There is a limited gamma field. According to Hansen², Wever believes the compound AuFe₃ exists. At low temperatures there are probably three phases, depending on the composition, namely: iron-rich (alpha) solid solution, compound and gold-rich solid solution. At higher temperatures, alpha, of course, changes to gamma. There is some disagreement as to the phase boundaries, but the following X-ray data on the solubility of Fe in Au, from Jette, Bruner and Foote³, are probably reliable:

Temperature, °C.	% Fe
300	3.5
450	6.9
600	12.5
724	17.2

With somewhat less accuracy these investigators determined that alpha iron will dissolve 2.05% Au at 724°C. and 0.6% Au at 600°C.

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³E. R. Jette, W. L. Bruner, and F. Foote, An X-Ray Study of the Gold-Iron Alloys, Trans., A.I.M.E., Inst. Metals Div., 1934, p. 354.

Helium-Iron—See Argon-iron

Hydrogen-Iron—The principal work on this system has been the determination of the solubility of hydrogen in iron at various temperatures. The results of Sieverts¹, Martin,² and Luckemeyer-Hasse and Schenck,³ given in Table I, are in fair agreement. These investigators all note the rapid increase in solubility of hydrogen in iron during the alpha-gamma transformation. Luckemeyer-Hasse and Schenck report an emission (that is, reduction in solubility) during the gamma-delta transformation which does not appear in the work of Sieverts. Luckemeyer-Hasse and Schenck believe the explanation for the greater solubility in gamma iron is found from Bragg's⁴ observation that in the face-centered cubic lattice there exists a "hole" in the center of the cube considerably larger than any free space in the body-

centered cubic lattice. In support of this it may be mentioned that Luckemeyer-Hasse and Schenck's curve for the solubility of hydrogen in delta iron is practically the prolongation of the curve for alpha iron.

Sieverts, whose tests were carried to temperatures beyond the melting point of iron, showed that molten iron has a much larger capacity for dissolving hydrogen than solid iron at the same temperature.

Using Sieverts' data for liquid iron, Luckemeyer-Hasse and Schenck have computed the absorption constant K for hydrogen in iron at atmospheric pressure and in weight per cent as follows:

$$\begin{aligned}\text{Alpha iron: } K &= 48 \times 10^{-6} \text{ } ^\circ\text{C.} - 17.2 \times 10^{-6} \\ \text{Gamma iron: } K &= 88 \times 10^{-6} \text{ } ^\circ\text{C.} - 37.2 \times 10^{-6} \\ \text{Delta iron: } K &= 60 \times 10^{-6} \text{ } ^\circ\text{C.} - 30.0 \times 10^{-6} \\ \text{Liquid iron: } K &= 275 \times 10^{-6} \text{ } ^\circ\text{C.} - 175.5 \times 10^{-6}\end{aligned}$$

The literature contains a number of references (5, 6, 7, 8, 9, 10) to iron hydrides. but experimental proof of their existence is not very convincing. Sieverts' considers

Table I
Solubility of Hydrogen in Iron at Atmospheric Pressure

Martin ²		Sieverts ¹		*Luckemeyer-Hasse and Schenck ³	
Temperature °C.	Solubility, cc. H ₂ per 100 g. Iron	Temperature °C.	Solubility, cc. H ₂ per 100 g. Iron	Temperature °C.	Solubility, cc. H ₂ per 100 g. Iron
....	....	....	....	310	0.1
....	....	....	....	350	0.2
....	....	....	....	400	0.25
....	....	409	0.4	....	....
....	....	....	....	410	0.3
440	0.30	....	....	460	0.6
....	....	514	0.84	....	....
522	0.75	....	....	600	1.15
....	....	620	1.32	....	....
649	1.49	724	1.99	....	....
772	2.10	775	2.25	....	....
....	....	....	....	800	2.35
....	....	827	2.71	....	....
....	....	852	2.95	....	....
....	....	878	3.53	....	....
896	2.83	899	4.36	....	....
....	....	904	4.28	900	3.0
....	....	....	....	905	3.06
....	....	....	....	910	4.8
924	4.46	930	4.82	....	....
....	....	981	5.37	....	....
1006	5.35	....	....	1000	5.5
1087	6.78	1033	5.89	....	....
1159	7.13	1136	7.06	....	....
....	....	....	....	1200	7.6
....	....	1250	8.68	....	....
....	....	1350	10.52	1300	8.3
....	....	....	....	1350	9.0
....	....	....	....	1400	9.35
....	....	....	....	1425	6.4
....	....	1450	12.08	1450	6.5
....	....	melting point	....	....	....
....	....	solid	13.44	....	....
....	....	liquid	27.86	....	....
....	....	1550 liquid	27.95	....	....
....	....	1650 liquid	32.2	....	....

*Figures read from curve.

the reaction of hydrogen absorption by iron powder at high temperatures and at pressures over 100 mm. mercury to be a simple solubility process since the gas concentration in the metal is proportional to the square root of the pressure, while at lower temperatures and with finely divided iron, adsorption takes place.

Esser and Cornelius¹¹ have shown that hydrogen causes an additional cusp on the thermal differential curve of iron in the vicinity of the A₁ transformation. No satisfactory interpretation of this effect has been advanced.

Luckemeyer-Hasse and Schenck¹² and Naumann¹³ studied the effect of hydrogen on the physical properties of iron. It was conclusively shown that hydrogen greatly reduces the impact strength of iron; although the hardness was not materially changed. Bending tests performed by Heyn¹⁴ show the embrittling effect of hydrogen on iron.

For the removal of hydrogen from iron Esser¹⁴ believes that repeated heating through the critical range is more advantageous than heating at higher temperatures, since the evolution of gas is favored by the atomic rearrangements during transformation.

Wedding and Fisher¹⁵ and Luckemeyer-Hasse and Schenck¹² believe that the pressure in iron due to liberation of hydrogen can be great enough to cause rupture of the metal.

An equilibrium diagram for the iron-hydrogen system has not yet been proposed.

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Lead-Iron—Isaac and Tammann¹ reported that liquid iron and liquid lead are practically mutually insoluble. The two metals are also mutually insoluble in the solid state. Tammann and Oelsen² gave the solubility of Fe in Pb as 2×10^{-4} to $3 \times 10^{-4}\%$.

References

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- ²G. Tammann und W. Oelsen, Die Abhängigkeit der Konzentration Gesättigter Mischkristalle von der Temperatur, *Z. anorg. allgem. Chem.*, 1930, v. 186, p. 277, Die Löslichkeit des Eisens in Blei, Silber, Wismut und Cadmium.

Lithium-Iron—See barium-iron

Magnesium-Iron—See barium-iron

Mercury-Iron—Most of the data on Hg-Fe alloys pertain to solubilities and agreement on this point is lacking. Joule¹ reported 0.14-1.4% Fe soluble in Hg, Gouy² stated the solubility as less than 0.01% Fe at 15-18°C., Richards and Garrod-Thomas³ gave the value 0.00134% Fe, Tammann and Kollmann⁴ gave $1.15 \times 10^{-11}\%$ Fe at 170°C., and Palmaer⁵ reported 0.00007% Fe between 20° and 211°C. Brill and Haag⁶ found by X-ray examination that Fe-amalgams containing up to 25% Fe consist of a

suspension of alpha iron in Hg and this fact may account for the conflicting results of other investigators.

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Osmium-Iron—Wever¹ lists this system (as well as the Ru-Fe system) as one wherein the gamma iron region is extended similar to the Fe-Ni system.

References

- ¹F. Wever, Ueber den Einfluss der Elemente auf den Polymorphismus des Eisens, Arch. Eisenhüttenw., 1928-29, v. 2, p. 739.

Palladium-Iron—The constitution of palladium-iron alloys was studied by Grigorjew.¹ The metals are completely soluble in each other in the liquid state and form a complete series of solid solutions, except there is perhaps a break at the composition corresponding to a compound of the formula FePd₃. Pd raises the temperature of the gamma-delta transformation and lowers the alpha-gamma transformation so that the diagram is quite like that for the Fe-Pt or Fe-Ni system.

References

- ¹A. T. Grigorjew, Les Alliages Palladium-Fer, Ann. inst. platine, 1931, v. 8, p. 25. (Russian); Über Legierungen des Palladiums mit Eisen, Z. anorg. allgem. Chem., 1932, v. 209, p. 295.

Platinum-Iron—The characteristics of this system, which is similar to the Fe-Ni system, have been determined by Isaac and Tammann¹ as follows:

1. Iron and platinum are mutually soluble in all proportions in the liquid state.
2. A minimum in the liquidus curve occurs at about 1510°C. and between 10 and 20% Pt.
3. Pt lowers the temperature of the alpha-gamma transformation progressively such that at about 52% Pt the gamma phase is stable at room temperature.
4. A compound FePt, also identified by Nemilow² is believed to exist between 65% and 90% Pt.

Kussmann³ studied the coefficients of linear (thermal) expansion between 20 and 70°C. of certain Fe-Pt alloys annealed at 650°C. He found that the coefficient behaves anomalously with composition in a manner similar to the Fe-Ni alloys. The coefficient is negative between 50 and 60% Pt and passes through a minimum at 55% Pt.

Nemilow² measured the hardness and temperature coefficient of electrical resistance of Fe-Pt alloys. In the annealed alloys he found a maximum in the coefficient versus composition curve at 50 atomic per cent Pt.

Graf and Kussmann⁴ studied the magnetic properties of Fe-Pt alloys and reported the presence of ferromagnetism in the region of 30-70 atomic per cent Pt.

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Potassium-Iron—See barium-iron.

Rhodium-Iron—Hansen¹ stated that it is probable that Rh and Fe form a complete series of solid solutions. Fallot² studied the alpha-gamma transformation in Rh-Fe alloys and found a minimum at 550°C. between 25 and 30% Rh.

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Rubidium-Iron—See barium-iron.

Ruthenium-Iron—See osmium-iron.

Selenium-Iron—In this system Fonzes-Diacon¹ and Moser and Doctor² have studied the compound FeSe, which is the analogue of FeS. Alsen³ identified the structure of FeSe as being the same as NiAs. The X-ray investigations of Hagg and Kindstrom⁴ disclosed that at 50 atomic per cent Se the compound FeSe occurs and the alpha modification is stable below 300-600°C. Above this temperature range the beta form is stable. Alpha FeSe has a PbO (tetragonal) structure while the beta phase has the NiAs structure. The beta phase can dissolve Se up to 57.5% Se. On the basis of the above consideration, Hansen⁵ has constructed an equilibrium diagram.

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- ⁵M. Hansen, Der Aufbau der Zweistofflegierungen, Julius Springer, Berlin, 1936, p. 731.

Silver-Iron—Petrenko¹ stated that silver and iron are mutually insoluble. Tammann and Oelsen² determined that silver will dissolve $4 \times 10^{-4}\%$ Fe at 1000°C. and $6 \times 10^{-4}\%$ at 1600°C.

References

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Sodium-Iron—See barium-iron.

Strontium-Iron—See barium-iron.

Tantalum-Iron—Jellinghaus¹ determined that Ta and Fe are mutually soluble in all proportions in the liquid state and a eutectic occurs at approximately 1400°C. between the iron-rich solid solution of 6-10% Ta and the compound FeTa. The solubility of Ta in alpha Fe decreases with decreasing temperature. According to Wever² the gamma field is closed at 4.25% Ta.

Recently the Ta-Fe system was studied by Genders and Harrison³. Their results appear to have been obtained with great care but are not concordant with the above. Genders and Harrison believe that errors in Jellinghaus' work are due to the presence of silicon (SiO₂ being reduced from the crucible by Ta). According to Genders and Harrison there are two eutectics, one at 20% Ta (approximately 1460°C.) between delta Fe solid solution and the compound Fe₂Ta, and the other at about 80% Ta between Fe₂Ta and the tantalum-rich solid solution. A lamellar eutectoid was found at 4.5% Ta and 1220°C. where delta breaks down to gamma (3% Ta) and Fe₂Ta. The solubility of Ta in gamma iron increases from about 0.6% at 974° to 4.5% at the eutectoid temperature. The solubility of Ta in alpha iron increases with temperature and amounts to about 1% at 974°C. Ta raises the temperature of the alpha-gamma transformation to 974°C. with 1% Ta but lowers the gamma-delta transformation to 1220°C at 3% Ta. The compound FeTa was not observed by Genders and Harrison, neither could they confirm the presence of the gamma loop.

References

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Tellurium-Iron—According to Oftedal¹ there is a compound FeTe having the NiAs structure in this system.

References

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Thallium-Iron—Isaac and Tammann¹ concluded from their work on this system that thallium and iron are mutually insoluble in both the liquid and solid states and form no compounds.

References

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Tin-Iron—The essential points of the iron-tin diagram as now known may be summed up as follows: 1. There is a miscibility gap in the liquid state between 51% and 80% Sn according to Edwards and Preece¹. 2. In the tin-iron system there is a closed gamma loop. According to Wever and Reinecken² the alpha-gamma transformation is eliminated at 1.9% Sn. 3. The solubility³ of Sn in Fe is about 18% Sn at 1132°C. The solubility decreases with lowering temperatures. 4. Three compounds, FeSn, Fe₂Sn, FeSn₂, form by peritectic reaction.⁴ A diagram of the Fe-Sn system has been published by Hansen⁴.

References

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⁴M. Hansen, Der Aufbau der Zweistofflegierungen, Julius Springer, Berlin, 1936, p. 740.

Titanium-Iron—The study of the iron-titanium equilibrium diagram is impeded by the difficulty of preparing pure Fe-Ti alloys. Lamort¹, whose alloys contained, in addition to TiN ("not more than 2%, as a rule less than 1%"), certain amounts of silicon (in three cases, 0.57, 0.90 and 1.12%) and aluminum (in three cases 1.15, 1.57 and 2.13%), determined that between about 5.4% to 22.2% Ti there occurs in this system a series of eutectiferous alloys consisting of the iron-rich solid solution and the compound Fe₂Ti (22.2% Ti). The eutectic was placed at 13.2% Ti and at 1298°C.

Seljesater and Rogers² studied the age hardening properties of iron-titanium alloys (0.5% to 7.1% Ti and containing "substantial amounts of Al and Si"), and concluded that the solubility of titanium in iron is approximately 6% at the eutectic temperature and 3% or less at room temperature.

Wever³ considers titanium in the group of metals that cause the formation of a gamma loop, and this is confirmed by Michel and Benazet⁴, who concluded that the alpha-gamma transformation disappears between 0.78% and 1.77% Ti.

By means of thermal analyses and X-ray examination Witte and Wallbaum⁵ investigated the iron-titanium system between 18% and 38% Ti. For the preparation of these alloys they used ferrotitanium of the composition 38.0% Ti, 0.7% P, less than 1.0% Si, less than 1.0% Al, 59.5% Fe; metallic titanium, melted (about 95% Ti); and Krupp WW iron. The amounts of impurities of the alloys are not stated. Witte and Wallbaum's results are not in agreement with Lamort, since they believe that the formula of the compound is Fe₂Ti (30.02% Ti). The melting point of Fe₂Ti was determined to be 1530°C., and its structure was reported to be isomorphous with MgZn.

References

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²K. S. Seljesater and B. A. Rogers, Magnetic and Mechanical Hardness of Dispersion Hardened Iron Alloys, *Trans., A.S.S.T.*, 1932, v. 19, p. 561.

³F. Wever, Ueber den Einfluss der Elemente auf den Polymorphismus des Eisens, *Arch. Eisenhüttenw.*, 1928-29, v. 2, p. 739.

⁴A. Michel et P. Benazet, Influence du Titane sur les Points de Transformation de l'Acier, *Rev. Mét.*, 1930, v. 27, p. 326.

⁵H. Witte und H. Wallbaum, Thermische und Röntgenographische Untersuchung im System Eisen-Titan, *Z. Metallkunde*, 1938, v. 30, p. 100.

Uranium-Iron—According to Hansen¹ the published work on the U-Fe alloys cannot be considered for determining their constitution since considerable amounts of carbon are present from the reduction of uranium ore by carbon. However, the work of Polushkin² may be mentioned, since it contains information as follows: 1. Uranium may form a compound Fe₂U. 2. Neither U nor the compound Fe₂U form solid solutions with iron. (Polushkin's alloys contained from 0.21 to 7.42% C and appreciable amounts of Si and V.)

References

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²E. P. Polushkin, *Alloys of Iron and Uranium*, Carnegie Schol. Mem., 1920, v. 10, p. 129.

Zirconium-Iron—From the work of Allibone and Sykes¹ and Vogel and Tonn² and others, Hansen¹ has published an equilibrium diagram which may be briefly described as follows: 1. The two metals are mutually soluble in all proportions in the liquid. 2. Two eutectics are formed one at 16% Zr and 1330°C. between gamma iron (0.7% Zr) solid solution and the compound Fe₃Zr₂, and the other at 88% Zr and 1350°C. with Fe₃Zr₂ and the beta Zr solid solution. 3. 0.3% Zr lowers the alpha-gamma transformation temperature to 835°C. The diagram published by Jänecke³ is in substantial agreement with the above.

References

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³M. Hansen, *Der Aufbau der Zweistofflegierungen*, Julius Springer, Berlin, 1936, p. 767.
⁴E. Jänecke, *Kurzgefasstes Handbuch aller Legierungen*, Otto Spamer, Leipzig, 1937, p. 113.

Equilibrium Relations in Binary Iron Alloys—The very considerable fund of information existing for binary alloys of iron has brought forth some quite worth while attempts to correlate the ninety-one possible systems. As early as 1890 Osmond¹ noted a relation between the atomic volume of an element and its effect in iron alloys on the alpha-gamma transformation.

An especially interesting discussion of the application of concepts of alloy-ability to binary iron systems was written by Wever.² He recognized four types of binary diagrams whose differences were based on the character of the face-centered cubic gamma region.

In Type 1 the gamma-delta transformation line rises to meet the liquidus line while the alpha-gamma transformation line is gradually lowered to the concentration axis. The Fe-Ni diagram (see page 386) is an example of the first type. Besides Ni, Co, Ru, Rh, Pd, Os, Ir, Pt and Mn belong in this group.

The equilibrium diagrams of Type 2 have the familiar gamma loop and the body-centered cubic alpha phase occupies the major portion of the solid region. The Fe-Cr system (see page 374) is an example of Type 2, to which Wever also assigns Be, Al, Si, P, Ti, V, Ge, As, Cb, Mo, Sn, Sb, Ta and W.

The diagrams of Type 3 have divergent transformation lines which end in heterogeneous regions as represented by Fe-C (see page 366). N, Cu, Zn, and Au are also placed in this group.

Type 4 has a constricted gamma field, illustrated by Fe-S. In addition to S, B, Zr and Ce are found in this classification.

Wever also developed a relation between the atomic radii of the elements and their effect on the polymorphism of iron as differentiated above. The values for the atomic radii were not those computed from the lattice constants of the pure elements. They were modified according to the ideas of Goldschmidt,³ first to take into account the degree of ionization of the atoms of the element in its crystal lattice and second to correct for variation in co-ordination number.⁴ When these values were plotted against the corresponding atomic number a wave-like curve resulted at or near the peaks of which were found most of the elements insoluble in iron, while all the elements that widen the gamma field were situated in the troughs. Those elements that restrict the gamma phase were located principally at intermediate positions.

In this relationship Wever noted that "not so much the absolute size of the atom itself as the position in the atomic radii curve, or better the position in the periodic system, decides to which of the four groups of equilibrium systems of iron an element belongs". This, of course, is the effect of valence which Hume-Rothery⁵ showed so conclusively in his study of binary alloys of silver. The point is illustrated in Fig. 1.

⁴Number of nearest neighboring atoms, that is, in a body-centered cubic arrangement each atom has 8 equidistant neighbors.

A somewhat different classification based on rather ingenious diffusion experiments was made by W. D. Jones.⁴ Using the principle that a diffusion boundary is an indication of a phase change, Jones' classification is as follows:

1. Al, Sb, As, Be, Cr, Mo, P, Si, Sn, Ti, W, U,^b V, Zn,^c when allowed to diffuse into iron between 1000 and 1300°C, produced a diffusion boundary with columnar ferrite grains and presumably, therefore, the binary system of each element with iron includes a gamma loop.

	I		II		III		IV		V		VI		VII		VIII		IX		X		XI		XII	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b	a	b
I																								
II	3 Li	4 Be			5 B	6 C			7 N	8 O			9 F											
III	11 Na	12 Mg			13 Al	14 Si			15 P	16 S			17 Cl											
IV	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni			30 Zn											
V	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd			48 Ag											
VI	55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt
VII	87 Fr	88 Ra	89 Ac	90 Th	91 Pa	92 U																		

Fig. 1—The types of binary iron alloys arranged in the periodic system of the elements. After Wever

Triangles: Elements insoluble in iron
 Square dots: Type 1 equilibrium diagrams
 Circular dots: Type 2 equilibrium diagrams
 Open squares: Type 3 equilibrium diagrams
 Open circles: Type 4 equilibrium diagrams

2. B, C, Co, Cu, Au, Ir, Ni, Mn and Ag, when allowed to diffuse into iron between 1000 and 1300°C., do not produce a diffusion boundary and presumably they tend to stabilize the gamma modification of iron.

3. Ba, Bi, Cd, Ca, Ce, Pb, Mg, Hg, K, Se, S, Ta and Te gave no evidence of diffusion in Jones' experiments, but he did not infer that no diffusion occurred.

Jones further noted that the heat of oxidation of each of the elements which inhibits the gamma phase is higher than that of iron and that, with the exception of manganese and boron, the converse is true.

The above correlations and others^{4, 7, 8} all contribute toward an understanding of the fundamental laws governing alloy systems. It is to be hoped more will be developed so that eventually our vast store of empirical knowledge of this subject may be completely systematized.

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^bSee Uranium-Iron above.

^cNote difference from Wever's classification.

a continuous curve formed by the lowering of A_1 and the raising of A_2 . The gamma field extends to 98.8 or 99% iron. The aluminum content required to close the gamma loop probably depends somewhat on the purity of the iron, particularly with respect to oxygen and carbon, as in the case of iron and silicon.²⁸

The dotted line of magnetic transformation is taken from Iwase and Murakami's results,²⁹ except that the A_2 point for iron has been definitely established at 769°C.²⁷ and the magnetic transformation curve consequently starts from this point. The A_2 transformation decreases slowly by the addition of aluminum up to 10%, and then rapidly until 16.5% content is reached, at room temperature.

More recently Sykes and Evans³¹ have shown that alloys in the region corresponding to the composition Fe_2Al (13.9% Al) "possess many interesting and hitherto unsuspected properties" depending upon whether the lattice structure occurs in a disordered or an ordered state. The change from the disordered to the ordered state can be prevented for compositions of less than 13.9% by quenching from 600°C. but not for higher aluminum contents.

The physical properties of iron-aluminum alloys up to 17% aluminum were investigated by Sykes and Bampfylde.³² They found that alloys from 0-5% aluminum are ductile and can be cold worked similar to pure iron. Alloys of 5-16% aluminum are brittle in ingot form and when cold. These alloys must be hot worked. Alloys above 17% cannot be worked.

Electrical resistivity curves show that alloys containing 12-16% of aluminum are affected by heat treatment whereas no effect occurs in those with from 2-12% aluminum. The general shape of the curves of the mean coefficient of expansion suggests that some form of transformation occurs in alloys having an aluminum content greater than 12% in the range of 500-600°C.

The lattice spacings of iron-aluminum alloys were studied by Bradley and Jay.³³ They found that both annealed and quenched alloys with from 0-10% aluminum have a random atomic distribution and show a linear increase in lattice spacing. The lattice spacings of alloys of 10-20% aluminum are anomalous and affected by heat treatment. Above 20% aluminum both the annealed and quenched alloys have the FeAl type of structure.

Alloys from 37-49.5% Aluminum—During solidification the solid solution ϵ is formed peritectically at 1210°C. (α solid solution + melt $\rightleftharpoons (\text{FeAl})_n \dots \epsilon$) which exists in the range from 49.5-40.5% Al and resolves into the θ and α solid solutions by the eutectoid reaction at about 1080°C. This eutectoid is of the lamellar type and is visible under the microscope in the unetched condition.

The line of eutectoid decomposition is shown by most of the earlier diagrams although within different concentration limits.

Alloys from 49.5-55% Aluminum—The solid solution θ , mainly consisting of the compound FeAl_3 , is formed peritectically at 1150°C. by the reaction between the melt and the ϵ phase (ϵ solid solution + melt $\rightleftharpoons \text{FeAl}_3 \dots \theta$). A noticeably large uniform range of the θ phase exists at the temperature just below the solidus though it becomes a smaller one at lower temperatures. The solid solution η , mainly composed of the compound Fe_2Al_3 , is formed also by a peritectic reaction (θ solid solution + melt $\rightleftharpoons \text{Fe}_2\text{Al}_3 \dots \eta$), at a temperature slightly lower than 1150°C.; this phase lies between 53 and 56% aluminum.

Kurnakow's³⁴ electrical conductivity measurements between 42.5-60.3% aluminum showed that these alloys have minimum conductivity and temperature coefficient and that there is but a slight difference in the conductivity values within this composition range. The possibility of single points corresponding to intermetallic compounds is therefore remote. Iwase and Murakami's diagram²⁹ showed a homogeneous phase between 43-59% aluminum which was considered a solid solution of iron in the compound FeAl_3 . This was, however, not in agreement with the thermal curves of alloys of this type shown by Gwyer.

Gwyer found in this range a decomposition in the solid state at 1158°C., which was, however, difficult to distinguish. Alloys containing 50-60% aluminum disintegrate to a powder within a few days when exposed to air.

Alloys from 55-59% Aluminum—The solid solution δ composed of FeAl_3 and existing at about 59% aluminum has a maximum melting point on the liquidus. The range of this solid solution at a high temperature is about 2-3% aluminum. A eutectic reaction is found to occur between the δ and η solid solutions, the eutectic temperature being slightly lower than that of the peritectic reaction: (Melt + $\theta \rightleftharpoons \eta$). The heterogeneous range between η and δ is confined to 56-59% aluminum.

Alloys containing 50-60% aluminum are viscous in the liquid and brittle in the solid state.

Alloy of 59.28% Aluminum—A slight maximum occurs in the liquidus curve. This alloy is homogeneous. Most investigators agree that this maximum corresponds to the intermetallic compound FeAl , although from electrical conductivity measurements by Broniewski there is no evidence of the existence of the compound FeAl . It is assumed that FeAl is a compound of the Berthollet type, whose chemical composition is not definite. This compound is extremely hard and brittle.

Alloys from 60-100% Aluminum—These alloys form a eutectiferous series. The eutectic alloy contains 98.11% aluminum with a freezing point of 653°C . This eutectic point was placed at 98-98.3% aluminum by different investigators at temperatures in the range between 648 and 655°C .

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Constitution of Iron-Carbon Alloys

By R. S. Archer*

Cementite—Iron and carbon form a hard, brittle, crystalline compound, the composition of which is represented by the formula Fe_3C . This compound is referred to as iron carbide, or cementite. It contains 6.68% carbon by weight. Cementite crystallizes in the orthorhombic system, the unit cell containing 4 Fe_3C groups. The lattice parameter has been determined by Westgren and Phragmen,¹ by Wever,² and by Shimura³ on cementite crystals obtained from spiegeleisen. (The crystals probably contained some manganese and were, therefore, not pure iron carbide). The average values reported by these investigators are: $a_0 = 4.51 \text{ \AA}$; $b_0 = 5.06 \text{ \AA}$; $c_0 = 6.74 \text{ \AA}$. The average value for density corresponding to these determinations is 7.73, which is in good agreement with the value 7.74 obtained by Benedicks and 7.66 by Honeyman. The positions of the iron and carbon atoms in the cementite crystal as determined by Hendricks from the data of Westgren and Phragmen have been accepted by Westgren⁴ as probably correct. On heating above 1100°C ., iron carbide decomposes rapidly to iron and graphite. Its melting point has therefore not been observed but has been estimated at about 2000°C . Cementite undergoes a magnetic transformation at about 200°C .,⁵ designated A_6 .

Graphite—Under certain conditions, some of the carbon of iron-carbon alloys is present in the form of graphite, which is a distinct crystalline modification of the element carbon. Graphite is soft and friable. Graphite formed by annealing, as in malleable castings, is commonly referred to as temper carbon.

Allotropy of Iron—(See "Physical and Mechanical Properties of Iron," p. 424, this Handbook, for more detail). Solid iron is crystalline in structure, belonging to the cubic system. There are two distinct crystalline modifications of iron which are distinguished from each other by the arrangement of the atoms within the crystals. Each modification is stable only within certain ranges of temperature.

Modification	Crystal Structure		Range of Stability, °C.
Delta	Body-Centered	Cubic	1535-1400
Gamma	Face-Centered	Cubic	1400- 910
Alpha	Body-Centered	Cubic	910 and below

The appearance of the new crystalline form on heating or cooling through one of the critical temperatures is accompanied by complete recrystallization.

Iron undergoes certain discontinuous changes in physical properties in the neighborhood of 770°C . In particular, there is a marked decrease in magnetic properties on heating, this change being completed at 775°C .⁶ A slight evolution of heat on cooling, and a corresponding absorption on heating reach maximum intensity at 768°C . These changes are not accompanied by a change in crystal structure or by any corresponding phase change in the iron-carbon alloys.

Metallic Solid Solutions—Many metals possess the ability to dissolve certain other elements in the solid state, forming solid solutions which in many ways are analogous to ordinary liquid solutions. Ordinary brass, for example, is a solid solution of zinc in copper. Among the distinguishing characteristics of metallic solid solutions are: (1) Absence of definite atomic proportions; (2) capacity for change in chemical composition without abrupt change in physical properties; (3) ability of the dissolved elements to diffuse under suitable temperature conditions; (4) attainment of physical and chemical homogeneity when sufficient opportunity for diffusion is allowed.

It is probable that all metallic solid solutions are characterized by the atomic dispersion of the dissolved elements. When the atomic volumes of the solvent and solute elements are similar, as in the case of iron and nickel, it seems that the solute atoms replace atoms of the solvent, the space-lattice of which is retained. When the solute atom is markedly smaller than the solvent atom, as in the case of carbon and iron, it is quite probable that the solute atoms are in between atoms of the solvent.

Ferrite—Alpha iron is capable of holding in solid solution considerable amounts of various elements, such as nickel, silicon, and phosphorus. The maximum solu-

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bility of carbon in alpha iron occurring at 723°C. (1333°F.) is approximately 0.035%.^{1, 4, 6} This decreases as the temperature falls to less than 0.01%^{10, 11} at room temperature. The varying solubility of carbon in alpha iron although slight, as shown by these figures, has appreciable effects on the properties of the iron-carbon alloys.

The term "*ferrite*" is applied to solid solutions in which alpha iron (or delta iron) is the solvent.

Austenite—Solid solutions in which gamma iron is the solvent are called *austenite*. Gamma iron dissolves carbon to a great extent. The maximum solubility at 2066°F. is 1.7%. This decreases with temperature to 0.80% at 1333°F.

Constituents and Phases—Those portions of an alloy which under the microscope appear to be definite units in the structure are called constituents. Thus the constituents of an annealed low carbon steel are ferrite and pearlite. Usually the term constituent is only applied to a portion of the alloy which appears homogeneous. Pearlite appears homogeneous at low magnifications, but at higher magnifications it is seen to be a mixture of alternate plates of ferrite and cementite. Another constituent, troostite, appears homogeneous at all except very high magnifications, at which it is seen to be similar in structure to pearlite but much finer. Sometimes the term constituent is applied to structural bodies which are easily seen to be mixtures, even at low magnifications. This is true of the austenite-cementite eutectic, called *Ledeburite*.

A phase is a portion of an alloy, physically and chemically homogeneous throughout, which is separated from the rest of the alloy by distinct bounding surfaces. The following phases occur in the iron-carbon alloys: Molten alloy, austenite, ferrite, cementite, and graphite. It will be noted that any of these phases may likewise be called a constituent. Not all constituents are phases, however, since some are mixtures and are not "physically and chemically homogeneous throughout."

Constitution—The constitution of an alloy is completely described when we state what phases are present and how much of each. The question of the arrangement of these phases is not involved. It is a sufficient description of the constitution of an annealed low carbon steel at room temperature, for example, to say that it contains 3% cementite and 97% ferrite, although a description of the structure of this steel might give the added information that it contains about 22% of pearlite and 78% of free ferrite.

The iron-carbon diagram deals only with the constitution of the iron-carbon alloys and not with their structure.

Equilibrium—The iron-carbon diagram represents alloys in a condition of equilibrium. It may be considered that a state of equilibrium exists in an alloy at any given temperature where exposure to that temperature for any further period of time does not produce any change in constitution, provided the temperature in question is sufficiently high to allow constitutional changes to go to completion. The test of equilibrium is that the same condition is reached, no matter from which side it is approached, whether heating or cooling.

How Diagram Is Plotted—In Fig. 1 the temperature is plotted vertically and composition horizontally. Any point in the diagram represents a definite alloy at a definite temperature. The carbon content of the alloy is shown on the horizontal axis directly below the point in question, while the temperature is shown on the vertical axis directly opposite the point.

The various lines of the iron-carbon diagram represent phase changes, as will now be described.

The Liquidus—The line "ABCD," called the liquidus, represents the beginning of solidification on cooling and the end of melting on heating. All points above this line represent alloys in a completely molten condition. All points below ABCD represent alloys partially or completely solid.

Solidification—Alloys containing from 0-0.55% carbon begin to solidify on cooling to the line AB by the separation from the liquid of crystals of delta iron containing in solid solution an amount of carbon indicated by the line AH. By this separation of delta iron, the melt is enriched in carbon until the peritectic line HJB is reached. If the composition is to the left of J, delta of composition H will undergo a peritectic reaction with the melt of composition B resulting in the solidification of austenite of composition J, and the amount of delta of composition H will be thus reduced. On further cooling to the line NJ, the delta ferrite will transform to austenite. If the composition is to the right of J, the delta of composition

H will transform to austenite of composition J and reduce slightly the amount of the melt of composition B. On cooling to JE, the molten phase will solidify to austenite. Alloys containing from 0.55-4.3% carbon begin to solidify on cooling to the line BC by the separation of austenite crystals from the liquid.

Alloys containing more than 4.3% carbon begin to solidify with the separation of cementite from the liquid, on cooling to the line CD.

The alloy containing 4.3% carbon is the eutectic alloy and solidifies entirely at the point C, with the simultaneous formation of austenite and cementite.

In the case of alloys containing 0.55-1.7% carbon, austenite continues to freeze out on cooling from JBC to JE. At JE the alloy is completely solid and consists of one phase, austenite.

In alloys containing from 1.7-4.3% carbon, austenite freezes out of the liquid from BC to EC. At EC there is some residual liquid, which is of eutectic composition. This liquid then solidifies at constant temperature, forming the eutectic mixture of austenite and cementite.

In alloys containing more than 4.3% carbon, cementite freezes out on cooling from CD to CF. At CF the residual liquid is of eutectic composition and solidifies at constant temperature.

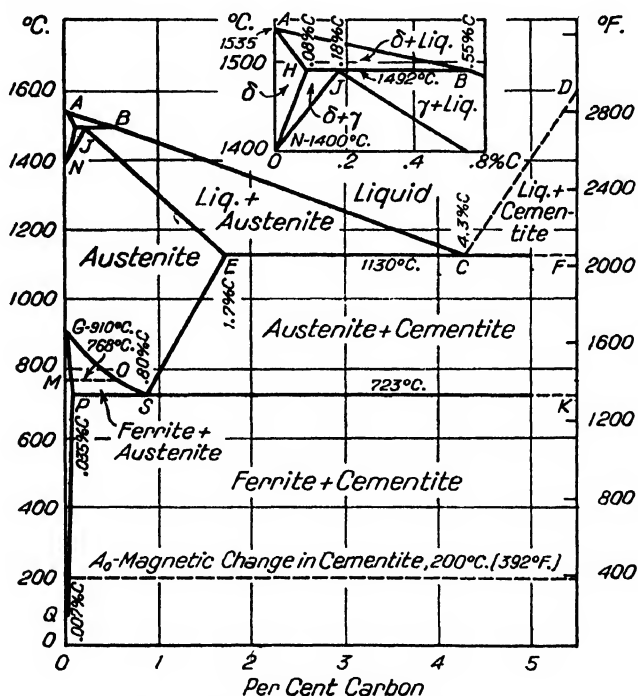


Fig. 1—Iron-Carbon Constitution Diagram.

The Solidus—The line AHJEF is called the solidus. Below this line all alloys are completely solid.

Ferrite Solubility Curve—The temperature at which alpha iron forms from gamma iron on cooling is lowered by the presence of carbon in solid solution in the gamma iron, that is, in austenite. This is represented in the diagram by the line GS, which shows that the temperature of formation of ferrite decreases from 1670°F. for pure iron to 1333°F. for an alloy containing 0.80% carbon. The formation of ferrite from the solid solution austenite is analogous to the precipitation of a salt from its solution in water. The line GS thus expresses the solubility of ferrite in austenite, and may be referred to as the ferrite solubility curve.

The dotted line MO represents the discontinuous change in the physical properties of alpha iron at about 768°C. It does not represent a phase change in the

iron-carbon alloys. The thermal arrest occurs at MO, and in alloys of higher carbon content is merged with the other arrests corresponding to the line OSK. Some diagrams show a sharp break in the ferrite solubility curve GOS at the point O. There seems to be sufficient evidence that GOS should be slightly curved, as shown in Fig. 1, but a sharp break at the point O is questionable. When austenite containing less than 0.80% carbon is cooled to temperatures represented by the line GOS, ferrite separates from solution. Since the ferrite is almost carbon-free iron, its separation results in an enrichment of the remaining austenite in carbon. This causes a progressive lowering of the temperature at which ferrite separates out, and the austenite constantly diminishes in amount and becomes richer in carbon. Consider a steel containing 0.40% carbon. At 1650°F. this steel consists entirely of austenite. On cooling to about 1435°F. ferrite begins to form, and continues to separate from the austenite as the steel cools further. When a temperature of 1333°F. is reached, the steel consists of one-half ferrite containing practically no carbon and one-half austenite containing 0.80% carbon.

Cementite Solubility Curve—At the eutectic temperature, 2066°F., austenite will hold 1.7% of carbon in solid solution. When austenite of this composition is cooled, cementite precipitates from solution. The solubility of carbon in austenite at various temperatures is shown by the line SE, which may be called the **cementite solubility curve**, as cementite is the phase which is precipitated.

When a steel containing more than 0.80% carbon is cooled from a temperature at which it is austenitic, cementite begins to deposit at the line SE. Since cementite contains 6.68% carbon, its precipitation causes a lowering of the carbon content of the austenite. This lowers the temperature at which cementite precipitates, and the cooling of the steel results in a progressive precipitation of cementite and a progressive decrease in the carbon content of the austenite. This continues until a temperature of 1333°F. is reached, and the residual austenite then contains 0.80% carbon.

The Eutectoid—No matter what carbon content is started with, austenite reaches a temperature of 1333°F. on slow cooling with a carbon content of 0.80%.

On cooling through this temperature austenite containing 0.80% carbon deposits simultaneously a mixture of ferrite and cementite. This mixture is called the **eutectoid**, from analogy to the eutectic.

The eutectoid temperature 1333°F. is the temperature at which austenite is simultaneously saturated with both ferrite and cementite. This is represented in the diagram by the intersection of the ferrite solubility curve GS with the cementite solubility curve SE, at the eutectoid point S.

Pearlite—With moderately slow cooling, the decomposition of austenite containing 0.80% carbon results in the formation of a constituent in which the ferrite and cementite occur as alternate thin lamellae. These lamellae refract light in a similar manner to the lines of a diffraction grating, giving the constituent a pearly appearance, from which it has received the name **pearlite**.

Reversibility of Phase Changes—The phase changes which occur on cooling, as described above, are reversed on heating. For example, on heating pearlite through 1333°F. the ferrite and cementite redissolve to form austenite. Considering the 0.40% carbon steel again, we have at room temperature a mixture of approximately equal parts of ferrite and pearlite. On heating to the line PSK (Fig. 1) this pearlite changes at constant temperature to austenite of eutectoid composition; the ferrite is unaffected.* On heating above PSK the ferrite gradually dissolves in the austenite until all of the ferrite is dissolved on crossing the line GS, and the austenite contains 0.40% carbon.

The Critical Points—The phase changes described liberate heat when they take place on cooling, and absorb heat on heating. These evolutions and absorptions of heat are shown by halts or arrests in cooling curves and heating curves, which indicate the temperatures at which the changes take place, and are usually called the **critical points**.

The method of designating the various points, which is borrowed from the French, needs a word of explanation. The halt or "arrest" in cooling or heating is designated by the letter A, standing for the French word *arrêt*. An arrest on cooling is referred to by the letters Ar, r standing for *refroidissement* = cooling. An arrest on heating is designated by the letters Ac, the c standing for *chauffage* = heating. The

*Except for dissolving the traces of carbon soluble below A1.

various arrests are distinguished from each other by numbers after the letters, being numbered in the order in which they occur as the temperature increases, as follows:

Arrest	Temp. °F.	Significance
A0	390	A magnetic change in cementite. Probably not a phase change. Hence shown in diagram by dotted line.
A1	1333	The eutectoid transformation.
A2	1414	A change in the magnetic and certain other properties of alpha iron. Not a phase change.
A3	1333-1670	The beginning of the precipitation of ferrite from austenite on cooling, or the end of its solution on heating.
A4	2552 (in pure iron)	The change from gamma to delta iron on heating, and vice versa on cooling.

When the critical point or the recalescent point is mentioned, it is usually the temperature of the eutectoid transformation, A1, that is meant.

Lag—The temperatures given above and in the diagram refer to conditions of equilibrium. Under practical conditions there is a delay or lag in the attainment of equilibrium, and the critical points are found at lower temperatures on cooling, and at higher temperatures on heating, than those given. That is, there is a difference between the Ar points and the Ac points. This difference increases with the rate of cooling or heating. The equilibrium temperatures correspond to very slow cooling or heating.

Classification of Alloys—Steels containing less than 0.80% carbon are called **hypoeutectoid steels**. Steel containing approximately 0.80% carbon is called **eutectoid steel**, or steel of eutectoid composition. Steels containing more than this amount of carbon are called **hypereutectoid**. Alloys containing less than 4.3% carbon are **hypo-eutectic alloys**; alloys containing more than 4.3% carbon are **hypereutectic alloys**. The alloy containing 4.3% carbon is the eutectic alloy.

Phase Fields—While the various lines of the constitution diagram represent phase changes, the areas bounded by these lines represent conditions of temperature and composition under which certain phases are stable. The phases stable within the various fields of the diagram are as follows:

Above ABCD	Liquid Solution	DCF	Cementite + Liquid
AHB	Delta + Liquid	NJESG	Austenite
AHN	Delta Iron Solid Solution	GSP	Ferrite + Austenite
HJN	Delta + Gamma	ESKF	Cementite + Austenite
JBCE	Gamma + Liquid	Under PSK	Ferrite + Cementite
		GPQ	Alpha Ferrite

Proportions of Phases—The amount of a certain phase present in a given alloy at a given temperature can be calculated in accordance with the following principle and examples: Determine the number of units on the composition axis between the points at which the alloy consists entirely of the phase in question, that is, the point at which the quantity of this phase is 100%, and the point at which the quantity of this phase has just decreased to 0.00%. Represent this number of units by the letter M. Determine the number of units on the composition axis between the composition of the alloy in question, and the point at which there is 0.00% of the desired phase. Represent this number by the letter N. Then the amount x of the desired phase, expressed in per cent, is

$$x = \frac{N}{M} \times 100$$

If the compositions expressed by the letters "M" and "N" are in weight percent, then the amount "X" of the desired phase will also be in weight percent. In the case of the iron-carbon alloys, however, the density of cementite is so close to that of iron, that "X" will also closely represent the volume percentage of the desired phase. In alloys whose constituents differ markedly from each other in density, a more general method of calculation must be employed which takes into account the densities of the various constituents.

For example, it is desired to calculate the amount of cementite in the austenite-cementite eutectic immediately after solidification; that is, at the eutectic temperature. With 6.68% carbon the alloy is 100% cementite. As the carbon is decreased the

amount of cementite decreases, becoming zero at 1.70% carbon, which is the amount soluble in iron at this temperature. The quantity M referred to above is then $6.68 - 1.70 = 4.98$. The eutectic alloy is $4.30 - 1.70 = 2.60$ units from the point of zero cementite. Then

$$\frac{2.6}{4.98} \times 100 = 52\% \text{ cementite in the eutectic alloy,}$$

$$100 - 52 = 48\% \text{ austenite in the eutectic alloy}$$

Description of Phases According to Origin—The austenite that freezes out of hypoeutectic alloys above the eutectic temperature is usually distinguished as **primary austenite**. The austenite of the austenite-cementite eutectic is referred to as **eutectic austenite**. Likewise, the cementite which freezes out of alloys containing more than 4.3% carbon is called **primary cementite**, and the cementite of the eutectic is called **eutectic cementite**. The ferrite which forms from hypoeutectoid austenite at GS is called **proeutectoid ferrite**, and the cementite which precipitates along SE is **proeutectoid cementite**. The ferrite and cementite of the eutectoid itself are described as **eutectoid** or **pearlitic**. Thus there are two kinds of ferrite from the structural standpoint, and four kinds of cementite distinguished by their origin.

Structural Constitution—The quantities of the structural constituents present in an alloy can also be calculated with the help of the equilibrium diagram, using the principle illustrated above.

Suppose it is desired to calculate the amount of pearlite in a 0.35% carbon steel at room temperature. The carbon content corresponding to 100% pearlite is 0.80%. Assuming that the solubility of carbon in iron at room temperature is zero, which is practically the case, the point at which the amount of pearlite decreases to zero is 0.00% carbon. Then $M = 0.80 - 0.00 = 0.80$.

$$N = 0.35 - 0.00 = 0.35$$

The amount of pearlite in the steel

$$= \frac{N}{M} \times 100 = \frac{0.35}{0.80} \times 100 = 44\%$$

The amount of ferrite in the steel = $100 - 44 = 56\%$.

A steel containing 1.7% carbon, after cooling at a normal rate to room temperature, is composed of pearlite and proeutectoid cementite. The amount of this cementite can be calculated as follows: The carbon content at which the structure would consist entirely of cementite is 6.68% (the composition of pure cementite). The carbon content at which the proeutectoid cementite decreases to zero is 0.80%. Then $M = 6.68 - 0.80 = 5.88$. $N = 1.70 - 0.80 = 0.90$. The quantity of proeutectoid cementite in the 1.70% carbon steel is then

$$\frac{N}{M} \times 100 = \frac{0.90}{5.88} \times 100 = 15\%$$

The amount of pearlite in the steel is $100 - 15 = 85\%$. Since 1.7% carbon is the maximum amount soluble in austenite, 15% is the maximum amount of proeutectoid cementite possible.

Effect of Other Elements—All commercial steels contain more or less manganese, phosphorus, sulphur and silicon. Most commercial steel also contains residual amounts of copper and nickel. The data on temperature and composition which are represented in the iron-carbon diagram refer to iron-carbon alloys containing extremely low amounts of other elements. The amounts of these other elements which are present in commercial steel may alter appreciably the location of the various lines in the diagram. When still larger amounts are present, even the form of the diagram may be substantially changed. The constitutions of various binary alloys of iron are discussed in the articles immediately following this one. It is hoped that it will later be possible to present complete data on the constitution of the ternary alloy systems comprising iron, carbon and one other element. The effect

of this other element on the constitution of the iron-carbon alloys will then be completely described.

Stable vs. Metastable Equilibrium—Under certain conditions the carbon of iron-carbon alloys occurs as graphite. This is favored by extremely slow cooling, a condition which in general favors the establishment of stable equilibrium. It is, therefore, generally considered that iron and graphite represent the ultimately stable phases of the iron-carbon system, and that the occurrence of iron and cementite represents metastable equilibrium. Accordingly, alloys which at various temperatures consist of austenite and graphite, or of ferrite and graphite, with no cementite, are said to constitute the **stable system**. Alloys containing cementite but no graphite, which have been described above, are said to constitute the **metastable system**.

Phases of Stable System—The phases of the stable system are: (1) Liquid alloy; (2) austenite; (3) ferrite; and (4) graphite. It will be noted that the first three of these also occur in the metastable iron-cementite system.

Effect of Composition on Graphitization—The formation of graphite is favored by the presence of silicon, nickel and aluminum. In practice it is difficult to produce graphite in strictly pure iron-carbon alloys. The occurrence of graphite in such products as gray cast iron, malleable iron, and tool steel is usually due to the presence of silicon.

Graphitization is opposed by the presence of carbide forming elements such as chromium and manganese. Sulphur as iron sulphide strongly opposes graphitization, but is inactive when present as manganese sulphide. The first additions of manganese, therefore, favor graphitization by neutralizing sulphur. For a given composition of alloy with respect to elements

other than iron and carbon, graphitization takes place more readily the higher the total carbon.

Diagram for Stable System—The constitution diagram of the iron-graphite system is shown in Fig. 2 in full lines, the dotted lines representing the equilibria of the iron-cementite system.

In the case of three lines, AC, AE, and GS, the dotted lines and full lines coincide. This is because these lines represent equilibria between those three phases which are common to the two systems.

The rest of the diagram, in which the dotted lines and full lines do not coincide, merely expresses the fact that at all temperatures the solubility of graphite in iron is less than that of cementite in iron. Accordingly the eutectic and eutectoid temperatures of the iron-graphite system are higher than for the iron-cementite system.

The diagram is qualitative in that it does not represent the exact differences in solubility and temperature. These differences are relatively slight. Wells¹² has made careful determinations in the region around the eutectoid, using alloys of high purity, and Mehl and Wells¹³ investigated metastable (iron-cementite) equilibria in the same alloys. They place the eutectoid at 0.80% carbon in the metastable system, and at 0.69% carbon in the iron-graphite system; the eutectoid temperature at 723°C. for iron-cementite, and at 738°C. for iron-graphite.

Graphite and Cementite Together—Both stable and metastable equilibria may be represented in the same alloy, as illustrated by the following example:

Well annealed malleable castings consist almost entirely of ferrite and graphite and, therefore, belong entirely to the stable system. Suppose a piece of malleable cast iron containing 2.40% graphite is heated to 1600°F. The graphite will begin to dissolve in the iron, forming austenite. This process will continue until the carbon content of the austenite reaches a value represented by a point where a 1600°F. horizontal intersects the graphite solubility curve S'E', that is, at about 1.00%. When this solution process comes to rest the alloy is in a state of equilibrium, the equilibrium belonging to the stable system. Now if the alloy is cooled slowly to room temperature, a rate of about 10-20°F. per hr. being required for

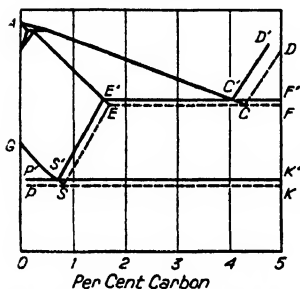


Fig. 2—Stable and Metastable Equilibrium Diagrams. The Dotted Lines Represent Metastable Equilibrium and the Solid Lines Represent Stable Equilibrium. For simplicity, some details which are not pertinent to the iron-graphite system are omitted from this diagram (see Fig. 1).

ordinary malleable, graphite will be reprecipitated. However, if the alloy is cooled moderately fast, as by air cooling, only a little graphite will be formed from the 1.00% of carbon dissolved in the austenite. Most of this carbon will precipitate as cementite, forming pearlite on passing through A_1 . This pearlite belongs to the metastable system.

Ordinary cast irons, which generally contain both graphitic and "combined" carbon, represent a combination of stable equilibrium, attained or approached at the higher temperatures, and metastable equilibrium, produced by the more sluggish phase changes at the lower temperatures.

Remarks—Attention is called to the fact that the diagram here given represents conditions of equilibrium in iron-carbon alloys of the highest purity available to the various investigators upon whose work the diagram is based. Small amounts of impurities have appreciable effects upon temperatures at which the phase changes occur, and it has not been easy to prepare and work with iron-carbon alloys of such purity that the impurities present could be said to have no appreciable effects. Oxygen, in particular, is difficult to eliminate. Temperatures are altered, and changes represented in the diagram as occurring at constant temperature may take place over an appreciable range of temperature. In commercial steels the pearlite change at A_1 , for example, takes place over a range of temperature instead of at a constant temperature, as represented in the diagram by the line PSK.

The carbon contents and temperatures which define the various points in the diagram have been selected after a review of the work of the various investigators in this field. The reader who has further interest in the subject is referred to a very thorough and critical review of the subject in the monograph on iron-carbon alloys.¹⁴

It will be noted that all of the lines in the diagram are drawn straight, with the exception of the line GOS. It is probable that most of these lines, with the exception of the horizontals, are curved, but it is considered that there is insufficient evidence at present on which to base the construction of lines having a definite degree of curvature. The line GOS, it seems, should be definitely curved in the direction shown and approximately to the extent shown.⁴

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Constitution of Iron-Chromium Alloys

By Edgar C. Bain* and Robert H. Aborn**

Introduction—The fundamental concept of an iron alloy system wherein the alloying element is more soluble in alpha or delta iron than in gamma iron, and which, therefore, has a limited composition range for stable austenite, is so essential to the understanding of the iron-chromium system that reports of the early investigators who did not recognize this possibility need not be considered here. Probably anticipated by Tammann¹ and certainly predicted by Hanson² and Oberhoffer³, the existence of the gradually restricted (and finally suppressed) temperature range of stability for the gamma iron solid solution was first definitely determined by Wever⁴. With Gianl and Reineken he constructed the equilibrium diagrams for the iron-silicon and the iron-tin systems which, like the iron-chromium series, exhibit the "austenite loop"; a very important contribution to ferrous metallography. Shortly thereafter, the same characteristic in the iron-tungsten and iron-molybdenum systems was independently discovered and announced by Sykes⁵ who accurately constructed their equilibrium diagrams, and the austenite loop in iron-chromium alloys was found by Bain⁶.

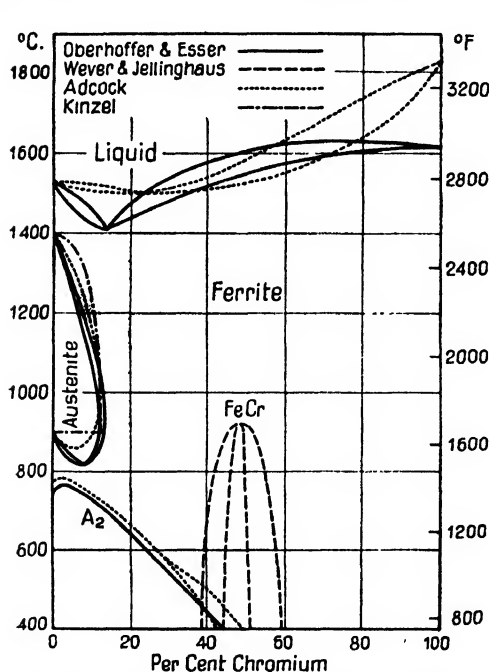


Fig. 1—Iron-Chromium Constitution Diagram contributed to by various investigators.

Fig. 1 illustrates the growth of the diagram as contributed to by various investigators.⁷ The original view that chromium raises the A_3 temperature even when present in small amounts was based upon tests on impure alloys and was rejected with further evidence. Recent studies by the present authors under proven equilibrium conditions and dilatometric researches¹⁰ corroborate the Oberhoffer and Esser³ loop rather than Kinzel's⁸ horizontal A_3 line. Adcock's⁹ liquidus and solidus appear more probable than that of Oberhoffer and Esser, although the melting point¹⁰ of chromium seems somewhat uncertain. Wever and Jellinghaus¹¹ corroborate the existence of the brittle compound. The region of the compound is left uncertain (dotted) in the diagram because of certain ambiguities in the interpretation of the data. As in the iron-aluminum and iron-silicon alloys, very large physical effects seem to result from a pre-precipitation stage of the compound formation and the representation of this condition in a phase diagram is still an undecided question.

Characteristics of the Iron-Chromium Alloy Series—The authors have drawn the diagram in Fig. 2 as representing a probable best compromise. While certain refinements will doubtless entail future revision, the diagram is not believed to be seriously in error. The principal characteristics of the iron-chromium alloy series are as follows:

1. The melting range shows a single noneutectiferous minimum, at which solidus and liquidus are tangent, characteristic of homogeneous isomorphous series.
2. Delta iron and chromium are completely miscible in all proportions in the solid state, and form therefore, at elevated temperature, a complete series of homogeneous solid solutions.

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3. Gamma iron, even at the temperature of its greatest chromium dissolving capacity (925-950°C.) holds only about 12.8% chromium in saturated solid solution.

4. Increasing chromium content rapidly lowers the A_4 or delta \rightleftharpoons gamma transformation temperature, and likewise in proportions up to about 7 or 8% lowers the A_2 or alpha \rightleftharpoons gamma transformation; beyond this, higher concentration of chromium, while it continues to lower the A_4 temperature, rapidly raises the A_2 temperature until A_2 and A_4 coincide.

5. The A_2 transformation which, for pure iron, occurs at a single constant temperature requires a range of temperature in iron-chromium alloys, a circumstance necessitating a two phase (alpha + gamma) region in the equilibrium diagram. This temperature range, however, of the mixed structure is narrow and vanishes at the single composition (about 7 or 8% chromium) corresponding to the minimum A_2 temperature. All compositions, excepting pure iron, show a temperature range for the A_4 transformation, with the corresponding delta + gamma field in the diagram.

The very circumstance of the disappearance of transformation in alloys carrying more than about 12.8% chromium forces the conclusion that alpha iron and delta iron are in reality the same phase of crystalline entity. This point is of sufficient significance to warrant consideration. If chromium be added continuously to iron, at for example, 800°C. (hence to alpha iron or ferrite) then no phase change is encountered even when an alloy of 18 or 20% chromium is reached. If such an alloy is heated to a very high temperature (1425°C.) no change of phase occurs; and if gradually the chromium content is reduced to zero, the same phase is still preserved and the final pure iron is in the so-called delta condition. The lattice parameter of the crystal unit of pure iron at this temperature (2.93Å) is in accord with the observed thermal expansion of alpha iron from its room temperature crystal dimension (2.860Å). Alpha iron and delta iron are therefore in reality the same allotropy.

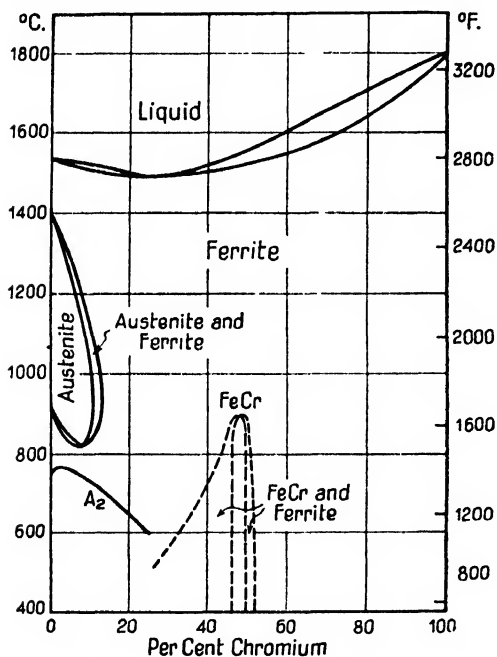


Fig. 2—Iron-Chromium Constitution Diagram representing best compromise from various investigators. (Bain and Aborn.)

6. The temperature of rapid magnetic change in iron (A_2) is, except for a possible slight elevation accompanying the first small additions, uniformly lowered by increasing chromium content.

7. In all probability a compound, FeCr, is formed in alloys carrying more than perhaps 30% and less than 55% chromium. The rate of the transformation of ferrite to this brittle phase (B constituent)¹² is extremely slow in pure alloys unless cold worked,¹³ but rapid in the presence of a few per cent of nickel and other elements. The rate of formation of FeCr is the more rapid the nearer the temperature is maintained to its upper limit of stability. The constituent when developed appears to be converted to ferrite at temperatures above about 900°C. even for the pure constituent, and at lower temperatures when it forms only part of the alloy. For example, a temperature of about 700°C. destroys the phase when developed in a 30% chromium alloy. The compound, as would be expected, is extremely hard and brittle, and is nonmagnetic. Although several investigators offer evidence for the existence of this compound (see references 13, 14, 15, 16, 17 and 19), Adcock has not been able to verify it in his purest alloys.

8. All iron-chromium alloys containing even up to about 40% chromium are

(in the absence of the brittle phase FeCr) definitely plastic even at ordinary temperature. The malleability and plasticity decreases with increasing chromium content and grain size. At high temperature the alloys are forgeable with chromium up to 60 or 70%; even pure chromium exhibits definite high temperature plasticity.

9. The alloys containing less than about 12.8% chromium, and therefore exhibiting allotropy, are definitely hardened by quenching from temperatures establishing the gamma iron solid solution. The higher chromium alloys in this range undergo greater hardening by quenching, which forms a carbonless martensite with definite acicular markings as observed microscopically. Alloys carrying more than about 5% chromium may be quenched from temperatures which establish the high temperature alpha iron solution (δ ferrite), without any transformation, to yield unchanged the high temperature structure. The allotropic change to austenite, and its reversion, is thereby obviated entirely.

10. Carbon, nickel, manganese, and cobalt when present in the iron-chromium alloys rapidly increase the maximum chromium solubility in the gamma iron solution (austenite); whereas silicon, tungsten, molybdenum, vanadium, aluminum, tantalum, and phosphorus, reduce the chromium solubility in austenite. The ternary iron-chromium-carbon system is relatively complex due to the formation of several different carbides and to the unusual circumstance of the existence at equilibrium of carbide and ferrite in contact at high temperature with no austenite.

11. When about 11.5% chromium is present in homogeneous solid solution in iron the resultant alloy is substantially unattacked in many oxidizing environments. The abruptness of the acquisition of this corrosion resistance from the standpoint of composition calls to mind the Tammann rule of eighths since the critical composition for this passivity is practically 1 atom of chromium to 7 of iron—1 in 8. The corrosion resistance is believed to be effected by a passive surface layer containing oxygen, and is a characteristic common to all members of the stainless steel family.

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Constitution of Iron-Copper Alloys

By J. L. Gregg* and B. N. Daniloff†

General—The iron-copper diagram has assumed a new importance because of the recent discoveries that marked precipitation hardening can be produced in the iron-rich alloys and that the quenching preceding the aging treatment need not be at all drastic, thus making it possible to harden the alloys by merely reheating the air cooled specimens to a temperature at which precipitation occurs. The diagram is also interesting because its liquid immiscibility field appears to be unique among metallic systems.

As a part of the Alloys of Iron Research program the literature on the alloys of iron and copper was reviewed by the authors, while at the Battelle Memorial Institute, and the results were published in the book "Alloys of Iron and Copper" in 1934. A thorough search of the literature in connection with this work has proved that the available data are not sufficiently reliable and consistent to permit the construction of an accurate and certain iron-copper equilibrium diagram, but what is believed by the authors to be the most probable diagram has been drawn and is described at right.

Review of Early Work on Iron-Copper Diagram—Though earlier workers had studied iron-copper alloys, an attempt to actually determine the iron-copper diagram was first made by Sahmen¹ in 1908. In disagreement with some of the earlier observers, notably Pfeiffer², he found that the alloys were completely miscible in the liquid state. Work of Ruer and Fick³ and Ruer and Goerens⁴, reported in 1913 and 1917 respectively, definitely established the fact that 2 liquid layers could occur in the iron-copper system. Presumably accurate thermal analyses, however, failed to indicate a horizontal portion of the liquidus required by the phase rule when alloys melt to form 2 conjugate liquids. In commenting on iron-copper alloys in 1925, Ostermann⁵ pointed out that the discordant results of the various investigators and the inconsistency with the phase rule would be explained if the region of liquid immiscibility approached but did not intersect the liquidus. This hypothesis was in part supported by the observation of Ruer and coworkers that the region of immiscibility narrowed as the temperature decreased. Experimental data secured by Müller⁶ also supported Ostermann's hypothesis, although Ruer⁷ was not convinced that the field of liquid immiscibility was closed at the low temperature. A recent investigation by Maddocks and Claussen⁸ indicated that there is no liquid immiscibility at temperatures as high as 1570°C. in alloys containing almost no carbon.

Iron-Copper Constitution Diagram—In the constitution diagram given in Fig. 1 the region of immiscibility is shown as closed at about 20°C. above the liquidus. As far as the authors are aware, this is the only known binary metallic system in which alloys of all compositions melt to form a single liquid but in which alloys within a given range of composition separate into two conjugate liquids as the temperature is raised. This behavior has been observed in a number of nonmetallic systems.

No compounds are formed in the iron-copper system, and the solid phases pres-

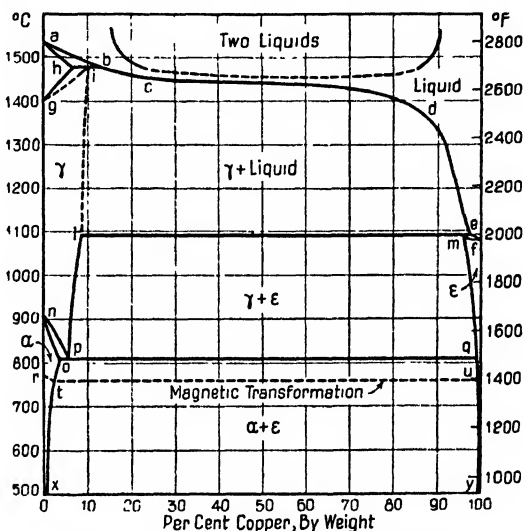


Fig. 1—Iron-Copper Constitution Diagram.

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ent are merely a solution of one component in the other. In the diagram they are described as follows:

- delta—iron-rich phase with body-centered lattice stable at high temperatures.
- gamma—iron-rich phase with face-centered lattice, the "austenite" of this system.
- alpha—iron-rich phase with body-centered lattice stable at low temperatures, the "ferrite" of this system.
- epsilon—the copper-rich phase, containing not more than 4% iron.

The iron-rich portion of the iron-copper system is strikingly similar to that of the iron-carbon system. Like iron-carbon alloys, in certain concentrations the melt reacts peritectically with the delta phase to form the gamma phase. The temperature of this reaction as determined by Ruer and Klesper⁸ is 1477°C. In the diagram, delta solid solution of composition h reacts with melt of composition b at this temperature to form gamma solid solution of composition i.

The Eutectoid—A eutectoid occurs in the iron-copper system in which the gamma solid solution is converted into alpha and epsilon solid solutions. The eutectoid point is shown as p in the diagram and the alpha and epsilon phases in equilibrium with the gamma phase at the eutectoid temperature are represented as o and q respectively. Ruer and coworkers found the eutectoid temperature to be 833°C. and located point p at 2.3% copper, but Buchholtz and Köster⁹ gave the temperature as 810°C.

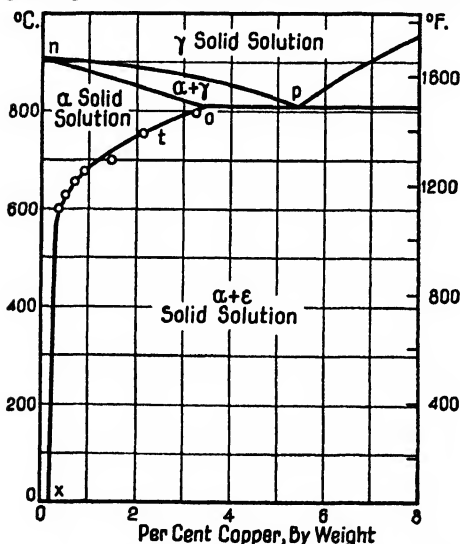


Fig. 2—Solubility of copper in alpha iron. (Buchholtz and Köster.)

phenomenon does occur. However, Vogel and Dannöhl¹⁶ in a recent publication reported that the solubility of copper in gamma iron is 8% at 1470°C. and increases to 8.5% at 1094°C.

A second peritectic reaction occurs at 1094°C. in which melt of composition e reacts with gamma of composition l to form epsilon of composition m, as was established by Ruer and coworkers.

The temperature of magnetic transformation, as determined by Ruer and coworkers, is shown by the line rtu.

The solubility of copper in alpha iron below the eutectoid temperature and the solubility of iron in copper decrease with decreasing temperature, thereby suggesting the possibility of dispersion hardening in both iron-rich and copper-rich alloys. As was shown by Hanson and Ford,¹⁰ the degree of dispersion hardening that can be produced in copper-rich alloys is not great, but recent workers, including Kinneer,^{11, 12} Nehl,¹³ and Buchholtz and Köster,⁹ have shown that marked precipitation hardening can be produced in the iron-rich alloys. It has also been found that the iron-rich alloys need not be drastically quenched in order to bring about supersaturation at room temperatures, and remarkable hardening can be produced by air cooling, followed by reheating in the neighborhood of 600°C.

and the concentration as 5.5% copper. The latter values were used in drawing the diagram, but it is not known whether or not they are more reliable than the others. A recent investigation by Norton¹⁵ indicated that the eutectoid was in the neighborhood of 850°C., but this transformation temperature was not determined with certainty.

Phases of Iron-Copper System—Line np corresponds to the A_1 line of the iron-carbon system. Along this line the alpha phase whose composition is represented by line no is formed on cooling. Line lp corresponds to the A_{cm} line of the iron-carbon system. Along this line, epsilon phase of composition mq is formed on cooling.

Line il, separating the gamma from the gamma plus liquid phase, has not been accurately determined. If its direction is as shown, certain alloys partially melt on cooling, and according to Ostermann⁶ this surprising

The solid solubility of copper in alpha iron as shown by xto in Figs. 1 and 2 is as given by Buchholtz and Köster. In a recent determination of this line by X-ray diffraction methods Norton found that the solubility of copper in iron at the eutectoid temperature and temperatures down to 650°C. was appreciably less than that indicated in the diagram. According to Norton the limit of solubility of copper in alpha iron at the eutectoid temperature (point O) is only 1.4%, and the solubility at 650°C. and lower is 0.35%.

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Constitution of Iron-Manganese Alloys

By Dr. V. N. Krivobok* and Dr. Cyril Wells†

General—Since the publication of the comprehensive studies of iron-manganese alloys, the last of which appeared in June, 1936, no further work appears to have been done and, consequently we are still lacking complete understanding of the iron-manganese system. For example, the relationship, under equilibrium conditions, between the epsilon phase (presently to be described) and other phases is not yet known.

In common with many metallic systems, alloys of iron and manganese exhibit a marked tendency for hysteresis between the phase transformations on heating and cooling. Thus, the study of equilibrium conditions at various temperatures is complicated and much care in interpreting experimental observations is required if erroneous conclusions are to be avoided.

The iron-manganese phase diagram is reproduced in Fig. 1. It is believed that this diagram represents most accurately the constitutional changes which take place in this system, and is based on the work of several investigators. Liquid plus delta, delta, delta plus gamma and liquid plus gamma fields are drawn from Gayler's data,⁴ while the remaining fields, indicating the changes in the solid state from the data of Walters, Wells and co-workers.⁴

The results obtained by Walters and Wells concerning the changes in the solid state of the manganese-rich series of alloys are in much closer agreement with the

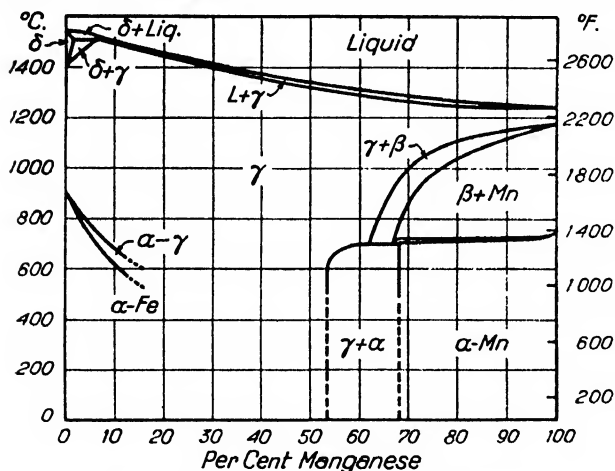


Fig. 1—Iron-Manganese Constitution Diagram.

Some specific information is still lacking, such as the limit of solid solubility for manganese in alpha iron.

Phases in the Iron-Manganese System—The characteristics of various phases that are found in practically carbonless iron-manganese alloys are given below. The regions occupied by such phases are clearly indicated in Fig. 1.

Delta—The delta iron-manganese solid solution has body-centered cubic atomic arrangement and is most probably of the replacement type.⁴

Gamma—The gamma iron-manganese solid solution has face-centered cubic lattice arrangement. The volume of the unit cell is increased with an increase in manganese concentration.⁵

Alpha—The alpha iron-manganese solid solution has body-centered cubic atomic arrangement, similar to that of delta iron-manganese solid solution. As in the

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⁴Probably this and all other solid solutions mentioned are of the replacement type, since the size of the atoms for iron and manganese are nearly identical.

work of Ohman¹ than with that of Gayler. It may now be definitely stated that the principal fields of the diagram and the reactions taking place in the iron-manganese system are well established, with the exception, however, of the epsilon phase which is discussed later. There still may be some doubt as to the accuracy of determined limits of temperature and concentrations. For this reason the alpha-gamma transformation in Fig. 1, and also the transformations taking place in manganese-rich alloys are shown with broken lines above certain concentrations.

gamma phase, the volume of the unit cell increases with increase in manganese concentration.³

Epsilon—The epsilon phase was only recently discovered by Schmidt.⁴ The atomic arrangement in this phase is found to be hexagonal close-packed. Although sufficient evidence concerning the nature of this phase is not available at present, it is likely that it is a solid solution and not an intermetallic compound.

The question of stability of the epsilon phase (and consequently its place in the constitution diagram) presents a controversial point. Some of the investigators believe that it is not a stable phase and should be regarded as quite comparable to martensite of iron-carbon alloys.⁵ Since, however, the fact of its formation in iron-manganese alloys under certain conditions (Fig. 2) is definitely established, its existence should be recognized.

Dilatometric Evidence—Fig. 2 is based on dilatometric evidence. The formation of epsilon from gamma on cooling and of gamma from epsilon on heating is clearly indicated.

It is to be observed that the hysteresis associated with the gamma to epsilon and the epsilon to gamma transformations is much less pronounced than in the case of the gamma to alpha and alpha to gamma transformations.³ In fact, the low hysteresis associated with such a low temperature transformation and involving such high melting point constituents is rather striking; it might be considered as at least some evidence in favor of stability of the epsilon constituent within certain temperature limits. Once the epsilon is formed, it persists to below room temperature, as dilatometric evidence indicates.

Alpha manganese-iron solid solution possesses a complex lattice structure with 58 atoms in the unit cell, of body-centered cubic type and with 29 atoms in a group at each lattice point. In pure manganese the allotropic change (from alpha to beta manganese) occurs at 742°C. According to Ohman the addition of iron does not, at first, materially change the temperature of transformation.

Beta manganese-iron solid solution has also a complex structure, cubic with 20 atoms in the unit cell. In pure manganese this phase is present at temperatures above 742 and below 1191°C.

Gamma manganese-iron solid solution has also a complex structure, cubic with 20 atoms in the unit cell. In pure manganese this phase is present at temperatures above 742 and below 1191°C.

Gamma manganese-iron solid solution is believed to have a face-centered tetragonal atomic arrangement with 4 atoms in the unit cell. In pure manganese it forms at 1191 and exists up to the melting point of manganese (1245°C.).

Gamma iron and gamma manganese are believed by some to form a continuous series of solid solutions, but Ohman suggests another possibility. The experimental data of Ohman¹ in regard to this question is not conclusive. No X-ray or microscopic evidence has been published indicating the presence of gamma iron and gamma manganese existing together in a two phase region.

The conclusion of Ohman that a narrow two phase region (gamma iron plus gamma manganese) may exist is based only on the fact that his data suggested a cubic lattice up to approximately 70% manganese and a tetragonal one from 70-100% manganese. Gayler's conclusions are in agreement with those of Ohman.

Phases, Iron End of Diagram—At the iron end of the diagram and at temperatures above 500°C. the phase relationship is quite simple (Fig. 1). Upon further lowering of the temperature the relationship becomes more involved, mostly because of the appearance of the epsilon phase.

Fig. 2 reproduces the results of the dilatometric studies regarding the relationship between various phases at the iron end of the diagram.⁶ The dilatometric method of analysis is quite adaptable to this system because of the definite volume changes that accompany the phase transformations. The same dilatometric method is particularly useful for the study of the epsilon phase,⁶ since the latter is not as

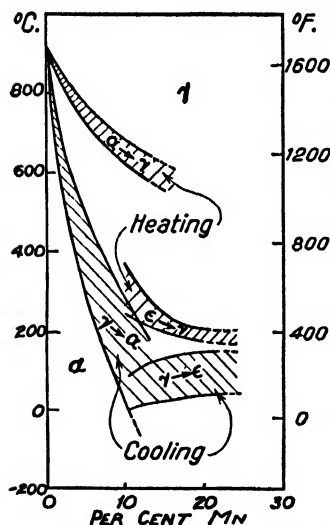


Fig. 2—Formation of epsilon from gamma on cooling and of gamma from epsilon on heating.

⁶For detailed description of volume changes see reference 3, part IV.

yet identified by means of a microscope. It will be seen from Fig. 2 that the line representing the upper part of the alpha to gamma transformation on heating agrees very well with data by Ohman. Similarly, on cooling, the lower limit of gamma to alpha transformation is practically the same as in Fig. 1. The existence of hysteresis previously mentioned is quite obvious. In this respect iron-manganese alloys are quite similar to those of iron-nickel.

The regions are indicated in Fig. 2 wherein the epsilon phase co-exists with gamma. The curves outlining the indicated areas do not represent the limits of the double phase regions, but merely the temperatures of the end of transformation (epsilon to gamma on heating and gamma to epsilon on cooling) as determined by dilatometric analysis. The experimental data do not permit a definite statement as to the type of reaction governing the relationship between gamma and epsilon phases. In fact, as has already been mentioned, the epsilon phase is held by some to represent metastable condition, which of course would exclude its presence in the equilibrium phase diagram.

Although Fig. 2 is not a constitution diagram, and consequently gives no information in regard to either the composition or the amounts of phases present, it shows that the addition of manganese to iron results in the following tendencies: First, a lowering of the gamma to alpha and alpha to gamma transformations, the former being affected more rapidly than the latter; second, as more manganese is added, a marked tendency of the alloys towards the formation of epsilon along with alpha as a product of the partially decomposed gamma phase; and third, formation of epsilon alone as a decomposition product. At the same time the amount of undecomposed gamma phase increases with the increase in manganese content.

Generally, a 10% manganese-iron alloy will contain on cooling alpha (predominating), some epsilon, and some untransformed gamma; a 13% manganese alloy will contain considerable amounts of all three phases; a 16% manganese alloy probably a little of alpha and considerable amounts of epsilon, and untransformed gamma. Beyond this concentration, the decomposition product will be almost entirely epsilon, the amount of which decreases as further additions of manganese are made. When concentration of manganese reaches about 40%, the gamma to alpha transformation, according to available information, does not take place at all. At this and higher concentrations, up to about 50% manganese, and at all temperatures from solidus down, the alloys consist of only one phase, gamma iron. At elevated temperatures gamma iron changes imperceptibly into gamma manganese with practically uniform changes in atomic volume.¹ Ohman, however, found a break in the lattice dimensions when exploring a complete series of alloys from 100% iron to 100% manganese, and, on the strength of his findings, indicated a heterogeneous field extending to the solidus line, the area of which is shown in Fig. 1 by broken lines. The type of reaction pertaining to this part of the system is shown, on a larger scale, in the upper right-hand corner of Fig. 1.

Eutectoids—Alloys of high manganese concentration show the existence of two eutectoid reactions; one, taking place at about 1000°C., in which the phases involved are gamma iron, gamma manganese, and beta manganese, and two, occurring at approximately 735°C. between gamma iron, beta manganese, and alpha manganese. The results of recent investigations of these alloys, using metallographic and X-ray methods fully substantiate the existence of the second eutectoid reaction.

Effect of Quenching on Phases—High temperature phases are retained, by quenching, much more easily in alloys of high manganese content than in alloys high in iron. In fact, quenching low manganese, high iron binary alloys seems to accelerate rather than inhibit the transformation to the low temperature phases. Hence, the study of the various phases and their relationship under equilibrium conditions is quite difficult. It is clearly shown by the complex structures of the low manganese iron alloys, when attempts are made to preserve high temperature phases by quenching.²

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Constitution of Iron-Molybdenum Alloys

By W. P. Sykes*

The most recent and complete reports on studies of this alloy system are those published by Sykes,^{1,4} Takei and Murakami,² and Arnfelt.³ The constitution diagram in Fig. 1 is drawn from the data included in these reports. As this diagram indicates, the system may be described as follows:

(a) By the addition of about 3% molybdenum the gamma form of iron is completely eliminated.

(b) The solidus and liquidus temperatures pass through a minimum of 1440°C. at about 36% molybdenum.

(c) At 1450°C. the alpha solid solution is formed by a peritectic reaction be-

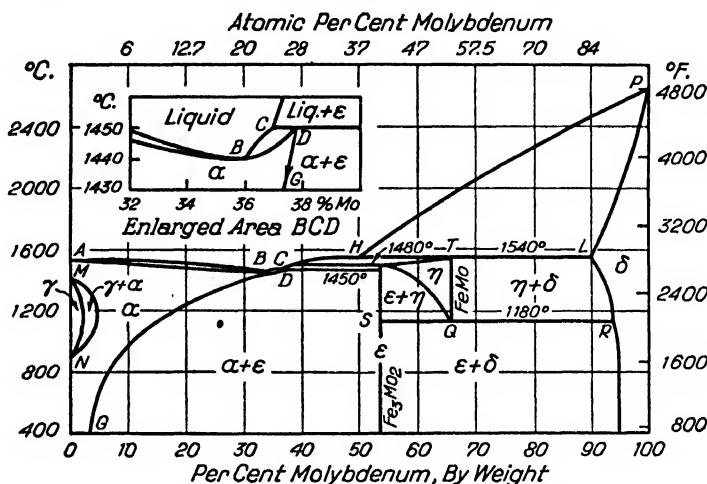


Fig. 1—Iron-Molybdenum Constitution Diagram.

tween the iron-rich liquid and the solid epsilon phase (Fe_3Mo_2). Some 38% molybdenum is dissolved in alpha at 1450°C. The solubility decreases to about 5% Mo at 500°C.

(d) Epsilon (Fe_3Mo_2) decomposes upon heating above 1480°C. to form an iron-rich liquid and a solid phase, eta.

(e) The eta phase appears to have a maximum molybdenum content of about 63%. This corresponds to the composition of an intermetallic compound having the formula FeMo .

(f) The eta phase in cooling undergoes a eutectoid transformation at about 1180°C. (SQR) the products being Fe_3Mo_2 and a molybdenum-rich solid solution containing about 6% iron. When heated above 1540°C. the eta phase decomposes into an iron-rich liquid and a solid solution of molybdenum (delta) containing about 11% iron.

(g) The solid solubility of iron in molybdenum decreases from about 11% at 1540°C. to about 5% at room temperature.

Properties of Pure Iron-Molybdenum Alloys—

The Rockwell and Brinell hardness numbers of the iron-rich alloys increase continuously with the addition of molybdenum up to about 40% by weight of molybdenum. Pure iron as quenched from 1425°C. has a Brinell hardness of about 60. An alloy containing 40% of molybdenum quenched from the same temperature has a Brinell hardness of about 450.

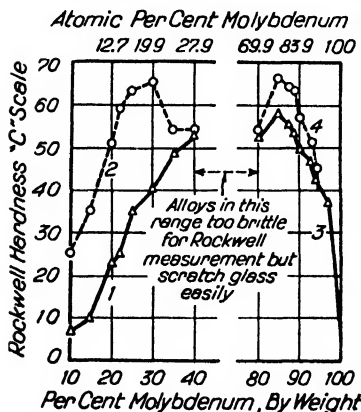


Fig. 4—Rockwell hardness of iron-molybdenum alloys.

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Compositions lying between 40 and 80% of molybdenum are composed largely of the intermetallic compounds and are glass-hard, but brittle. Compositions within the solid solutions ranges at either end of the system are markedly susceptible to precipitation hardening as shown by Fig. 2. Those alloys containing about 20% molybdenum will develop a Brinell hardness of 500-550 by aging at 625°C. for 20 hr. after having been quenched from 1400°C. The hardness so developed will persist over a long period at temperatures up to 650°C.

Due to their normal coarse grained structure, however, these alloys are relatively brittle and consequently, in their present stage of development, have a decidedly limited field of application.

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Constitution of Iron-Nickel Alloys

By Paul D. Merica*

The structure and equilibrium of the binary iron-nickel alloys have engaged the attention and interest of metallographers from the earliest days of the science when Osmond¹ presented the first constitution diagram of this series. Exhibiting a marked case of temperature hysteresis of transformation change in the alloys containing up to 34% nickel, and a curious anomaly in magnetic and elastic behavior of the alloys containing between 30 and 78% nickel, it is not strange that this series should have been the subject of so much study and discussion through the intervening years. Even today there are many questions regarding the iron-nickel equilibrium that are far from being solved or clearly understood.

The diagram reproduced in Fig. 1 is a composite based upon the work of most of those cited in the references, but chiefly: Hanson and Hanson²⁷ (transformations); Hanson and Freeman²⁸ (liquidus and delta region); and Honda and Miura²⁹ (irreversible transformations).

The equilibrium above 900°C. is clear. The temperature interval of freezing is not known with accuracy, but it is small. The freezing point displays a flat minimum at above 65% nickel.

In the solid state the alloys exist in three solid solution phases as follows:

Delta—Body-centered cubic lattice; parameter similar to that of alpha; exists within the field a c b.

Gamma—Face-centered cubic lattice; parameter varies nonadditively over that of nickel 3.517×10^{-8} cm. to 3.588×10^{-8} cm. at 39 atomic per cent of nickel, then decreasing to 3.575×10^{-8} cm. at 28.6 atomic per cent of nickel; exists at all temperatures beyond 34.4% nickel, at temperatures above e f for lower nickel contents and occasionally within area e f h i.

Alpha—Body-centered cubic lattice; parameter varies nonadditively from that of iron (2.86×10^{-8} cm.) to 2.875×10^{-8} for 32% nickel-iron; exists below e i and occasionally within area e f h i.

The delta and alpha phases are

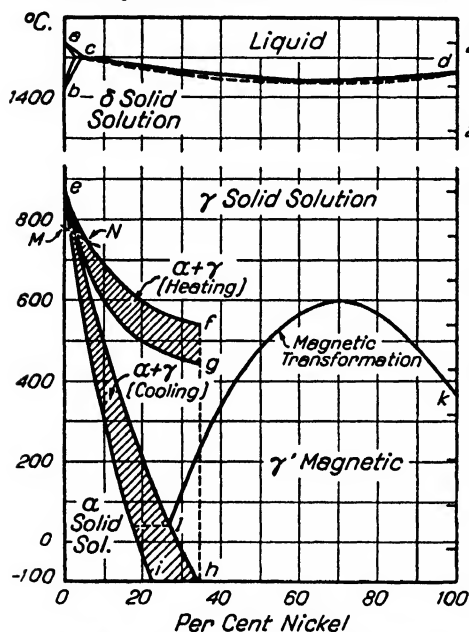


Fig. 1—Iron-Nickel Constitution Diagram.

similar in all respects and should be regarded as the same phase with separated temperature ranges of stability.

Below 34.4% nickel the γ phase, upon cooling, suffers a transformation to the α phase, and because of the marked temperature lag between cooling and heating this has been called the "irreversible" transformation, and the alloys, the "irreversible" steels. Due to the marked temperature hysteresis of this transformation the true or equilibrium temperature position is not known. It is indicated on the diagram by the two temperature ranges actually observed on slow cooling and on slow heating.

The opinion is that these two temperature ranges (e f g and e h i) represent in reality one range of heterogeneous equilibrium, which lies somewhere between the two and which is the equilibrium range of the transformation and of the stable existence of both the γ and the α phases. That there is such an equilibrium temperature range of duplex phase structure is evident from a consideration of meteor structure. Below 780°C. the two phases γ and α are distinguished by the fact that

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the former is para, while the latter is ferromagnetic. The magnetic method has been widely used as a means of identifying the two. The line MN represents the temperature of the A_2 magnetic transformation, which is known only approximately.

Beyond 34.4% nickel the alloys suffer a magnetic transformation shown on the diagram by the line 1 k, but it is the present opinion that this does not correspond to a phase transformation. The chief evidence for this point of view is that of X-ray analysis which has demonstrated that there is no change in lattice type in passing through the transformation 1 k, and no discontinuous change in lattice parameter. The evidence therefore seems to support the view that whereas the "irreversible" transformation is a true phase transformation, definite and clear, the "reversible" one is associated with changes within the atom or perhaps within a small group of atoms²³ which does not affect primarily the lattice organization and is hence not a true phase transformation.

This transformation is thus similar to that of iron at A_2 and to that of nickel. In consequence of their reversible transformation, these alloys have been called the "reversible" nickel steels or ferronickels.

The reversible transformation also proceeds in the alloys of lower nickel content insofar as they contain the γ phase as indicated on the diagram. Alloys having between 26 and 34% nickel may therefore undergo either the "reversible" or the "irreversible" or both transformations, depending on their past thermal history.

Between 30 and 78% nickel the magnetic transformation is the origin of the so-called "anomaly" of the "reversible" ferronickels. Associated with it are marked but apparently quite continuous changes in all physical properties, particularly density (dilatation or expansion) and elasticity. At 36% nickel there is such a pronounced arrest in the thermal expansion below the magnetic transformation that industrial use has been widely made of the alloy, under the name Invar.²⁴

The simple conception outlined above of the nickel-iron equilibrium below 900°C. is not shared by all authorities. The principal point of dispute is the nature of the "reversible" transformation.

Benedicks²⁵ believes that there is an actual phase change associated with the reversible transformation between 30 and 78% nickel, which explains the dilatation and contraction observed on aging the alloys showing the dilatation anomaly. Those who share this belief are inclined to suspect the existence of a eutectoid transformation: $\gamma \rightarrow \alpha$ plus magnetic γ' , which has been placed variously at 0°C. and 345°C., although no direct evidence of this transformation is available. In some iron-nickel meteors, structures have been observed strongly suggestive of eutectoid structure, but this is not necessarily adequate evidence of eutectoid transformation. Chevenard^{26, 27} believes that the reversible anomaly is associated with a molecular (but not a phase) transformation involving the formation and dissociation of the compound Fe_2Ni (34.4% nickel). He has pointed out the significance of the fact that it is at this composition that the irreversible transformation ends.

It is evident from this discussion that the irreversible alloys are subject to heat treatment in the same sense and in much the same manner as steel. The segregate of α phase resulting from its separation from γ resembles the structure and the mode of formation of martensite. These alloys are often called martensitic nickel steels, since they are fairly hard even after air or slow cooling.

The reversible alloys are not affected in the usual sense by heat treatment and are only moderately hard under all conditions.

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Constitution of Iron-Nitrogen Alloys

By John T. Norton*

General—Iron and nitrogen combine over a limited range of compositions to form solid metallic alloys. The maximum nitrogen content which can be obtained is about 11% by weight. It must be understood that an equilibrium diagram cannot be set up for this system without resorting to 3 dimensions, because the stability of the various phases is profoundly influenced by the nitrogen pressure. With this limitation in mind, it will be possible to set up a constitution diagram which will represent to a certain extent the relations between the phases of this system.

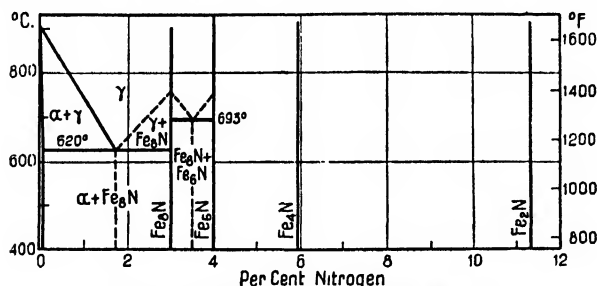


Fig. 1—Sawyer's Iron-Nitrogen Diagram.

When iron is treated with nitrogen gas in its molecular form, it is possible to obtain alloys with only a fraction of 1% of nitrogen. Even with pressures of the order of 100 atmospheres, little increase in nitrogen content is found. However, by the use of dissociated ammonia gas, elementary or monatomic nitrogen is obtained with an effective

nitrogen pressure corresponding to a very high value; under these circumstances, it is possible to form compounds of much greater nitrogen content. In the formation of the phases containing nitrogen, the diffusion rate of the nitrogen plays an important part, particularly at the lower temperatures where this rate is low. Consequently, in order to obtain a uniform distribution of nitrogen it is necessary to use samples having a very small cross section, such as powder, wire, or thin sheet, so that the composition will be the same in every part of the sample.

Iron-Nitrogen Constitution Diagrams—The first systematic attempts to set up a constitution diagram for this system seem to have been made independently by Sawyer¹ and Fry². These diagrams redrawn to the same scale are shown in Figs. 1 and 2.

Sawyer's Iron-Nitrogen Diagram—Sawyer employed microscopic and thermal analysis and his samples consisted of thin disks. The low nitrogen end of the diagram resembles that of the Fe-C system. He shows a solubility of nitrogen in alpha iron of about 0.03% by weight. The eutectoid

point occurs at about 1.8% nitrogen by weight and at a temperature of about 620°C. Sawyer's thermal analysis curves on heating indicated another eutectoid at a temperature of about 700°C. He concludes that the first eutectoid is formed from the alpha solid solution and the compound Fe₃N and the second between Fe₃N and Fe₂N. In the case of his nitrized disks, he decides that the outermost layer is Fe₂N, and that the two intermediate layers are Fe₃N and FeN.

Fry's Iron-Nitrogen Diagram—Fry's diagram is based on microscopic examination and magnetic measurements. The low nitrogen end is similar to that shown by Sawyer except that an increasing solubility with increasing temperature is indi-

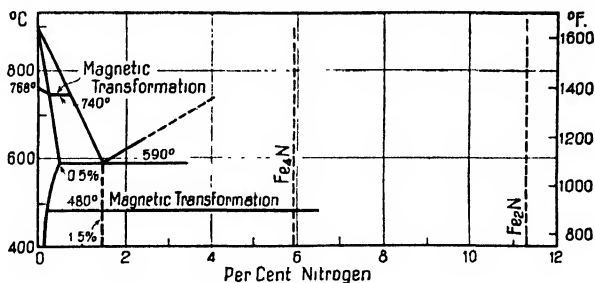


Fig. 2—Fry's Iron-Nitrogen Diagram.

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cated. He places the solubility limit of nitrogen in alpha iron as 0.015% at room temperature and about 0.5% at the eutectoid temperature of 580°C. The eutectoid composition is 1.5% nitrogen and is believed to be a eutectoid of the alpha solid solution and the compound Fe_3N . It has been named Braunitz. In the case of nitrized blocks, he observed two layers which he called Fe_3N and Fe_4N , but does not indicate the relations between these two compounds. Fry also mentions a phase resembling martensite in certain quenched samples.

Epstein's Iron-Nitrogen Diagram—The work of Epstein², which is really a modification and extension of the work of Sawyer and Fry, is based upon microscopic and thermal methods, together with some X-ray data (Fig. 3). The low nitrogen

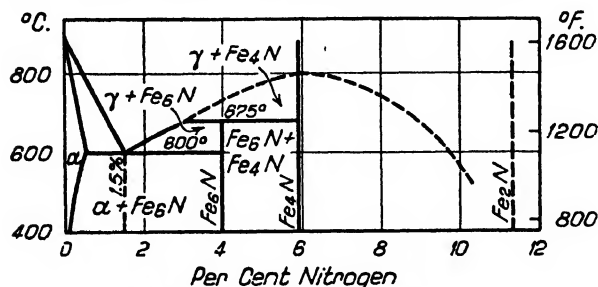


Fig. 3—Epstein's Iron-Nitrogen Diagram.

portion of Fry's diagram is generally confirmed. Epstein finds the two series of thermal arrests on heating which were found by Sawyer but, because the microscope does not show the appearance of a eutectoid between the intermediate and inner layer of nitrides, he suggests that a peritectoid reaction takes place corresponding to the decomposition of Fe_4N , the innermost layer

of nitride. The intermediate layer of nitride corresponding to Fry's outer layer is called Fe_3N by Epstein and the thin outer layer is supposed to be Fe_2N . The X-ray data are not particularly conclusive.

X-Ray Determinations—Because of the possibility of nitrizing a fine powder to a substantially uniform nitrogen content, the X-ray diffraction method seems to be particularly suited to the study of the phases present in this system and their ranges of homogeneity. Two such investigations have been carried out independently by Eisenhut and Kaupp³ and by Hägg,⁴ which are generally in good agreement. Eisenhut and Kaupp (Fig. 4) place the maximum solubility of nitrogen in alpha iron as 0.42%. The eutectoid temperature is found to be 591°C. with a nitrogen content of 2.35%. The existence of two compounds is claimed by these workers. The first, which is stable over a narrow range in the vicinity of 5.9% of nitrogen, has a face-centered structure and is designated as Fe_3N . This phase, called gamma prime, has a cell size somewhat larger than, and evidently not continuous with, the gamma phase, which seems to be a simple solid solution of nitrogen in gamma iron. The second compound has its iron atoms arranged in a hexagonal close-packed structure and is stable at room temperature from about 8% of nitrogen up to the maximum limit of the system at 11.3%. This compound is designated as epsilon and believed to be Fe_2N . The compound Fe_3N is supposed to decompose at 650°C. into the gamma and epsilon phases. It is interesting to note that in certain samples quenched from the gamma range, a tetragonal structure is found which is very similar to the tetragonal martensite recently found in the iron-carbon system.

In the work of Hägg,⁴ the results are in substantial agreement with those of Eisenhut and Kaupp (Fig. 5). Hägg, however, finds indication of another phase, orthorhombic in structure beyond the epsilon phase. The high nitrogen limit of the epsilon phase

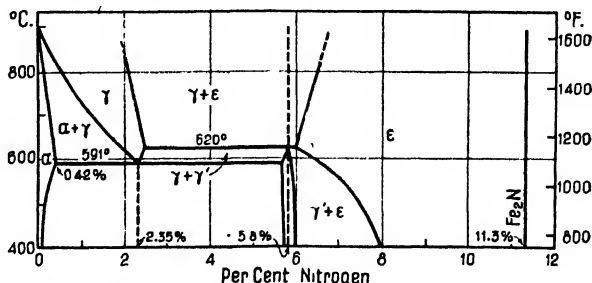


Fig. 4—Eisenhut and Kaupp's Iron-Nitrogen Diagram.

is about 11% nitrogen and the low nitrogen limit of the new phase is set at about 11.3% nitrogen. The theoretical composition of Fe_3N corresponds closely to the low nitrogen end of the orthorhombic phase.

Conclusion—A study of the work of these several investigators indicates the extreme difficulty of obtaining satisfactory working conditions. Nevertheless, certain aspects of the system appear quite definitely established. The alpha and gamma phases can be considered as true interstitial solid solutions of nitrogen in alpha and in gamma iron. The gamma prime phase seems to be definitely the compound Fe_3N and the nitrogen atoms have been located⁶ in the interstices of the close packed iron lattice. Undoubtedly there is a more definite relation than is shown

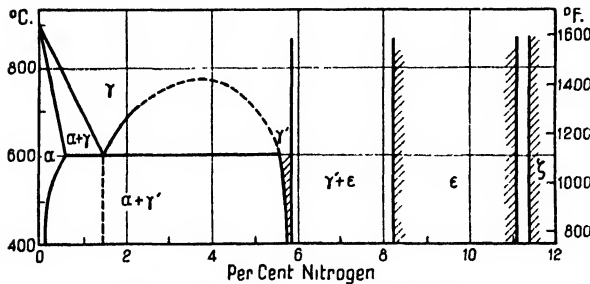


Fig. 5—Hägg's Iron-Nitrogen Diagram.

by the present diagrams between the gamma and the gamma prime phases, and this point merits further investigation.

nitrogen atoms are situated in the interstices of a lattice made up of iron atoms in what is essentially close packing. This undoubtedly depends upon the difference in size between the two kinds of atoms. It has been shown that practically all structures of this type have pronounced metallic properties. The X-ray evidence shows that definite compounds of the formulae Fe_3N and Fe_4N do not exist in this system.

Much work remains to be done to settle the details of this interesting system and a careful correlation of microscopic and X-ray evidence would be most helpful. The relations between the phases at the higher temperatures are still rather in doubt and a further study of the "nitrogen martensite" seems to have very promising possibilities because of its similarity to the analogous phase in the iron-carbon system.

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Alloys of Iron and Oxygen

By Dr. C. H. Herty, Jr.*

Oxygen in Steel—Throughout this article the term "iron-oxygen alloys" is used to denote iron oxide (probably FeO) dissolved in iron. It is realized that the term may not be correct but it does express fairly satisfactorily the intended meaning.

The element oxygen is found alloyed in iron in varying amounts in all steels. Oxygen exists in steel either as iron oxide (FeO) in solid solution, in small amounts of manganese oxide (MnO) in solid solution, or as nonmetallic matter distributed throughout the steel. The oxygen in this nonmetallic matter generally consists of manganese oxide, silica, and alumina, as such or in various combinations. If special deoxidizers are used, there will generally be small amounts of resultant oxides present in the steel. Oxygen in these forms, however, is not to be considered as alloyed with the iron, as it is present as a nonmetallic inclusion.

In all steel making processes iron oxide is dissolved in the steel at some stage of the melting. In the basic electric furnace the amount present is at a minimum, whereas in the open hearth furnace and in the Bessemer converter there may be as high as 0.50-0.60% FeO dissolved in the liquid steel. Upon deoxidation the amount of iron oxide is reduced to an extent depending entirely upon the type and quantity of deoxidizers used.

From a commercial standpoint, alloys of iron and oxygen are of little importance. However, it is necessary to have a high oxygen content in steel to reduce the carbon to a low concentration. Oxygen is, therefore, of considerable importance in the manufacture of very low carbon steels where the desired factor is low carbon rather than high oxygen. In this respect, oxygen may be considered a necessary evil.

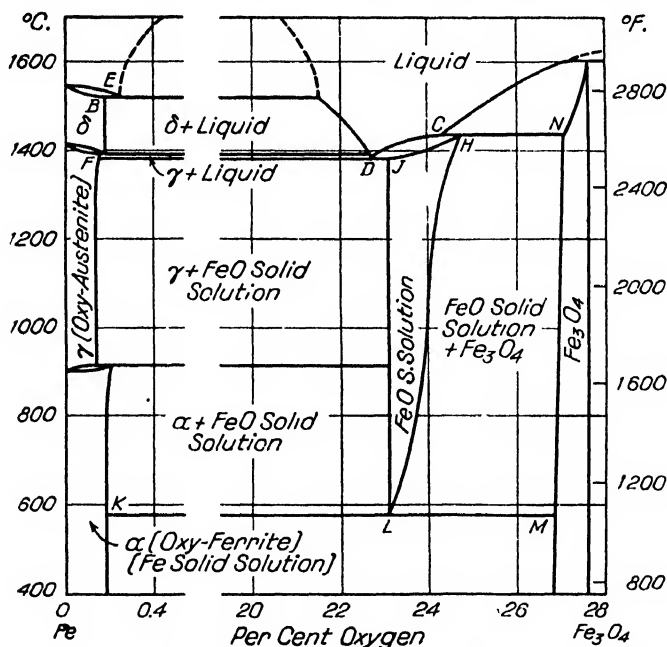


Fig. 1—Iron-Oxygen Alloys Constitution Diagram.

Constitutional Diagram of the Iron-Oxygen Alloys—Iron oxide lowers the melting point of iron approximately 10°C . when 0.94% FeO (0.21% oxygen) is present.¹ The solubility of iron oxide in iron is 0.94% at the melting point.² With increasing temperature above the melting point, the solubility increases and at 1600°C . the solubility is 1.37%. In commercial steels the iron oxide in liquid steel is less than

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the amounts stated, so that the finished steel contains from traces to 0.30% FeO. The solid solubility of iron oxide in iron is about 0.22%¹—an estimate based on microscopic evidence, and therefore to be considered merely an approximation. In a recent investigation, Krings² found the solid solubility of oxygen in iron to be 0.11% (0.494% FeO) at 715°C.

The constitution diagram of the iron-oxygen alloys, as determined by Vogel and Martin³ from various sets of data, is shown in Fig. 1.

Hot Working of Iron-Oxygen Alloys—Alloys of iron and oxygen forge well at high temperatures. Austin⁴ found that the alloys were difficult to work in the neighborhood of 900°C., but this was not confirmed by other investigators. Cain⁵ has found that oxygen in the presence of considerable amounts of sulphur causes steel to be red short, but that if the sulphur content is very low the steel is not red short up to fairly high oxygen contents. Tritton and Hanson¹ and Bureau of Mines investigators⁶ found no difficulty in hot working iron-oxygen alloys, and in both these cases the sulphur content was very low—below 0.010%. Austin gives no sulphur values for his alloys, and it is possible that the red shortness might have been due to a combination of oxygen and sulphur.

Effect of Iron-Oxide on the Physical Properties of Steel—Iron-oxygen alloys, according to Austin,⁴ are fairly resistant to corrosion in air, being better than mild steel, but they are more easily corroded in water and in weak acid than mild steel or wrought iron. Austin found that the 900°C. critical point was lowered slightly, but this was not checked by the work of Tritton and Hanson, who found no change in critical points.

The iron-oxygen alloys are brittle under impact testing.^{1, 2} The hardness increases slightly with increasing oxygen content^{2, 4} and the ductility decreases with increasing oxygen content.¹ Very high oxygen contents make iron cold short.¹ The electrical resistivity of iron is increased considerably by oxygen²; apparently this increase is due to the FeO in solid solution as the resistivity is unchanged over a considerable range of oxygen contents above this solid solubility limit.

The ultimate strength of iron is not affected by the oxygen content, but the elastic limit is lower than reported values for pure iron.²

According to Yensen and Ziegler,⁶ oxygen has a great effect on the magnetic properties of iron. Yensen⁷ states that high silicon steels used for magnetic purposes probably owe their excellent properties to the extremely low oxygen content rather than to the high silicon content. The age hardening of steel is increased by increasing its oxygen content.

Iron-oxygen alloys when carburized show structures in which the cementite is always massive and very little pearlite is present, when observed under the conditions of the McQuaid-Ehn test.⁸

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Constitution of Iron-Phosphorus Alloys*

By Louis Jordan†

The constitution diagram for iron-phosphorus alloys has been investigated up to only 30% phosphorus. Fig. 1 is the diagram as given by Haughton⁴. In its general form, this diagram agrees rather well with that portion of the diagram above 800°C. and up to 21% phosphorus, given by Konstantinow³. Konstantinow, however, indicated no field of gamma solid solution. Stead's¹ still earlier classification of iron-phosphorus alloys is consistent with Haughton's diagram. Saklatwalla's² constitutional diagram appears to be in error in several respects.

The iron-phosphorus liquidus falls from the melting point of iron to a eutectic of the alpha solid solution with Fe_3P at 1050°C. and 10.2% phosphorus. It then rises to a maximum of 1370°C. at 21.7% phosphorus, which is the composition of Fe_2P .

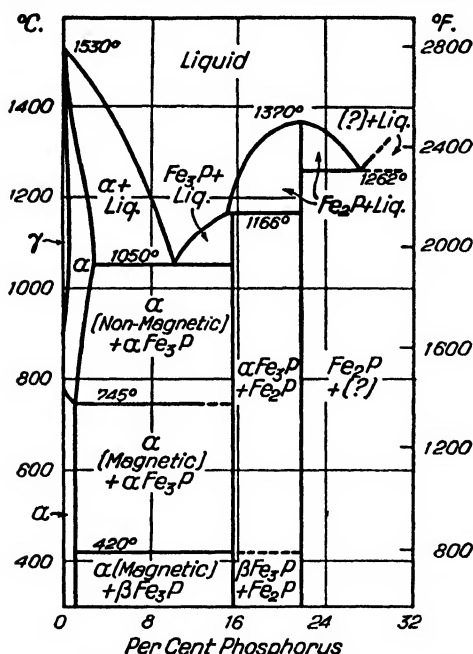


Fig. 1—Iron-Phosphorus Constitution Diagram (Haughton).

narrow two¹ phase field (represented in Fig. 1, however, as a single line).

Magnetically determined heating and cooling curves show the A_2 transformation in all alloys up to 13% phosphorus and a second magnetic point at 420°C., which is attributed to a transformation in Fe_3P similar to the A_0 in Fe_3C . Consequently this magnetic point at 420°C. is indicated in the diagram as continuing to the composition Fe_2P .

Hägg¹⁰ from X-ray analyses has assigned to the compound Fe_3P a body-centered tetragonal lattice and to Fe_2P a hexagonal lattice of the dimensions $a = 5.852 \text{ \AA}$ and $c = 3.453 \text{ \AA}$. He also found some evidence indicating the existence of FeP . Friauf¹¹ confirmed Hägg's results for the structure and lattice dimensions of Fe_2P . Two higher phosphides, FeP and FeP_2 , were prepared by Franke, Meisel, and Juza¹². Meisel¹³ determined lattice constants for FeP_2 . Roth, Meichsner and Richter¹⁴ have given heats of formation for Fe_3P , FeP , and FeP_2 .

Köster¹⁷ observed precipitation hardening in iron-phosphorus alloys containing over 1.2% P when quenched from 1000°C and reheated to 450-600°C.

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During this rise the liquidus curve breaks at the peritectic temperature, 1166°C., and at a phosphorus content slightly below 15.6%, which is the compound Fe_3P . From the maximum of 1370°C. the liquidus again falls to a second eutectic at approximately 27% phosphorus and 1262°C., which is a eutectic between Fe_2P and a constituent as yet unidentified.

Haughton determined the limits of solid solubility of phosphorus in iron between the melting point of iron and the eutectic line at 1050°C. by heat treatment and microscopic examination of the specimens, and also from the eutectic line down to 600°C. by both metallographic examination and thermal analysis. The solubility of phosphorus at the eutectic temperature is 2.8% and at the A_2 point is 1.1% (A_2 is at 745°C. in a 1.1% phosphorus alloy).

The solution of phosphorus in iron rapidly lowers the A_2 transformation and raises the A_3 . The two lines join at about 1050°C. and 0.5% phosphorus which gives an enclosed field of gamma solid solution. The boundary between the fields of gamma solid solution and nonmagnetic alpha solid solution is a

Phosphorus as a Steel Alloying Element—Phosphorus has recently been recognized as a useful alloying element in certain steels.²¹ It raises the yield strength and improves the resistance to atmospheric corrosion in low-carbon, low-alloy steels.²²

Ferrophosphorus—Ferrophosphorus has some use as an addition to certain open hearth steels which are to be rolled to sheets, particularly for light gages. A small amount of phosphorus in the steel tends to prevent sticking of the sheets. Ferrophosphorus also may be added to a cupola charge when the pig iron is too low in phosphorus to meet the casting requirements. Two grades of the alloy are made^{12, 13, 14}, a 17-19% alloy and a 23-25% alloy. The latter is an electric furnace product while the former may be produced in the blast furnace.

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The Constitution of Iron-Silicon Alloys

By Bradley Stoughton* and Earl S. Greiner**

Since the publication of the initial constitutional diagram of iron-silicon alloys by Guertler and Tammann,¹ in 1905, a number of investigators have studied this system and proposed revised constitutional diagrams. The literature relating to these investigations prior to 1933, has been critically reviewed in an Alloys of Iron Research Monograph² and a constitutional diagram of the iron-silicon system proposed. The portion of this diagram relating to alloys containing from 14-33.4% silicon has been modified in accordance with the results of a later investigation by Jette and Greiner.³ The revised diagram is shown in Fig. 1. The parts of this diagram which have not been definitely established are designated by asterisks.

The Iron-Rich Field—As shown in Fig. 1, silicon raises the A_1 transformation and lowers the A_2 transformation of iron. This results in a closed gamma loop having a limit at 2.2% silicon at 1170°C.⁴

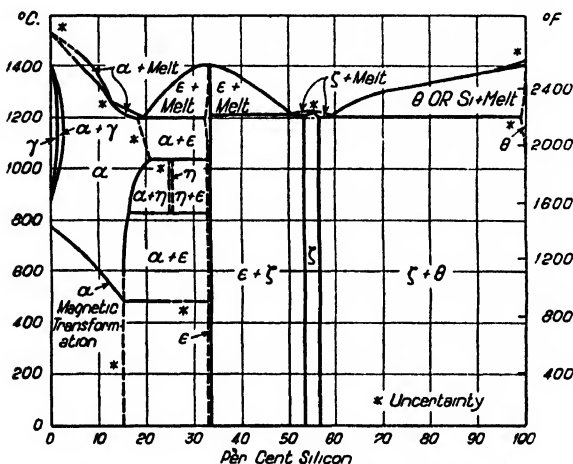


Fig. 1—The iron-silicon constitution diagram.

temperatures below 800°C., exhibits a discontinuity at about 4.7% silicon (9 atomic per cent) as shown in Fig. 2, and have advanced two hypotheses as possible explanations of their data in addition to the following generalizations:

"1. In the range between 0 and approximately 6 atomic per cent silicon (0-3.1 weight per cent) completely homogenized alloys should have properties that vary regularly in a way that would be expected of a series of solid solutions.

"2. In the region of 9 atomic per cent silicon (4.7 weight per cent), or perhaps between 6 and 9 atomic per cent, irregular behavior may be expected.

"3. In the range above 9 atomic per cent silicon, regular variation in the properties should again be expected up to 25 atomic per cent, but the absolute values of the quantities measured will probably indicate that the alloy is less 'typically metallic' as the composition approaches Fe_3Si .† (Since there is no conclusive evidence that Fe_3Si exists as a compound, it is simply regarded as a distinguishing point in the solid solution.)"

The Remainder of the System—The diagram shown in Fig. 1 indicates that several intermediate phases exist in the alloys containing more than 15% silicon. These phases are as follows:

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†14.4% Si.

The solubility of silicon in alpha iron⁴ (Fig. 1) is 15.2% at 600°C., increases to 20.4% at 1030°C. and decreases to 18.5% at 1200°C. The solubility limit for temperatures above 1030°C. is uncertain due to disagreements in the available experimental data, and has not been determined for temperatures below 600°C. The discontinuities in the solid solubility curve, resulting from phase transformations, occur at 16.6% silicon at 825°C. and 20.4% silicon at 1030°C.

By an X-ray investigation of the iron-rich iron-silicon alloys, Jette and Greiner³ found that the curve of lattice constant (a_0) versus atomic per cent silicon, for

Designation	Wt. % Silicon	Corresponding Chemical Formula	Structure
Eta	25.1	Fe_2Si_3	(Unknown)
Epsilon	33.4	FeSi	Cubic ^a
Zeta	53.5-56.5	.....	Tetragonal ^a

The eta phase (Fe_2Si_3), formed by a peritectoid transformation, is stable between 825 and 1030°C. However, the transformations occurring at these respective temperatures are sluggish. As a result, the eta phase may occur in these alloys below 825°C. or above 1030°C. if equilibrium has not been attained. The epsilon phase (FeSi), and the zeta phase, formed directly from the respective liquids on cooling, are

reported by Haughton and Becker⁷ to be stable at all temperatures to 0°C. Phragmén^{8, 9} has shown the zeta phase to have a tetragonal structure corresponding to the compound FeSi_2 (50.1% silicon), and considers the compound to have some of the iron atoms in the lattice replaced by silicon atoms, in order to form a stable phase. This explains the results obtained by Haughton and Becker,⁷ who found the homogeneous zeta phase extends from 53.5-56.5% silicon.

The solubility of iron in silicon is shown in Fig. 1 as being very small, which is in accordance with the results of Phragmén,⁸ and of Haughton and Becker.⁷ Murakami¹⁰ however, has reported a solubility of 4% iron in silicon.

Magnetic Transformations—According to Haughton and Becker,⁷ silicon

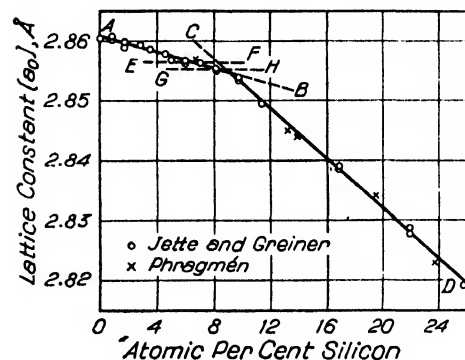


Fig. 2—Relation between lattice constant (a_0) and composition of iron-silicon alloys (Jette and Greiner).

lowers the alpha phase magnetic transformation (A_2) to 490°C. at 14.5% silicon, while further additions to 25% silicon do not change the transformation temperature. Murakami¹⁰ reported the alpha phase magnetic transformation at 450°C. in alloys containing from 16-30% silicon. Since Jette and Greiner⁴ have shown the alpha phase to be stable below 825°C. in the alloys containing from approximately 15-33% silicon, the magnetic transformation should occur in the alloys containing up to approximately 33% silicon, as shown in Fig. 1.

A magnetic transformation at 90°C. in the alloys containing from 16-30% silicon, was reported by Murakami.¹⁰ Later, Haughton and Becker⁷ found the temperature of this magnetic change to be 82°C. This transformation has been associated with the eta phase (Fe_2Si_3), but since this phase has been found to be unstable below 825°C., the magnetic transformation at 82 or 90°C. probably would not have been observed if the alloys had been in equilibrium.

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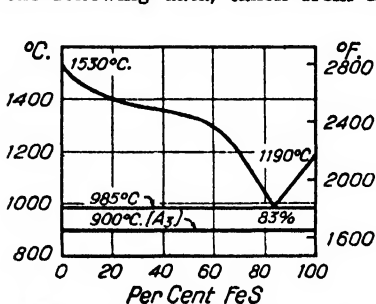
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Constitution of Iron-Sulphur Alloys

By G. F. Comstock*

The elements iron and sulphur form a compound FeS which contains 36.5% sulphur. Since for practical consideration in the metallurgy or metallography of iron and steel it is unnecessary to deal with alloys of higher sulphur content, this discussion will be confined to the alloys of iron and iron sulphide (FeS).

Nearly all authorities seem to be agreed that the system Fe-FeS is a simple eutectiferous one, and there is fairly general agreement in regard to the complete miscibility in the molten state. The constitution diagram has been determined by Friedrich,¹ by Loebe and Becker,² and more recently by Kozo Miyazaki,³ who took special precautions to avoid contamination by oxide. These diagrams agree closely. Starting with the freezing point of pure iron at 1530°C., the liquidus descends in an irregular curve to the eutectic at 985°C., then rises to the freezing point of FeS at 1190°C. The form of the liquidus curve may be reproduced quite closely with the following data, taken from Miyazaki's paper:



Constitution Diagram for Iron-Sulphur Alloys (Miyazaki).

With 20.9% FeS, the liquidus is at 1404°C.; with 61.34% FeS, it is at 1295°C.; the eutectic contains 83% FeS; and with 98.63% FeS the liquidus is at 1183°C.

The shape of the liquidus curve given by Benedicks and Löfquist⁴ is similar, but they state that the eutectic contains 30.9% sulphur, or 84.6% FeS. Sauveur⁵ states that this eutectic contains 85% FeS and melts at 950°C. McCance has given the eutectic temperature as 980°C. Friedrich showed the eutectic to contain 85% FeS and to melt at 983°C., and the melting point of FeS at 1171°C. Shibata found the melting point of FeS to be 1163°C. within 4° plus or minus,⁶ instead of 1190°C., according to Benedicks and Löfquist. However, these values

are in fair agreement, and probably Miyazaki's determinations can be accepted as practically correct.

In regard to the solubility of sulphur or FeS in solid iron, the information available is not definite. By electrical resistance measurements Miyazaki showed that the solubility must be less than 0.5% FeS, and from microscopic observations, he concluded that it was "practically zero at ordinary temperature." Benedicks and Löfquist state that "the solubility of sulphur in solid iron may be estimated at about 0.015-0.020% sulphur," and give good authority for this estimate in their recent book.⁶ The solubility probably increases somewhat with rise in temperature. Wohrman agrees that only about 0.05% FeS is held in solid solution by pure iron at atmospheric temperature. Some investigators seem to have found a slight lowering of the critical points of iron due to the presence of sulphur, but in general this effect has been inappreciable.

Iron sulphide (FeS) is easily recognized in polished sections of iron or steel by its bright yellow color, and its property of being readily attacked by boiling alkaline sodium picrate. Cementite, also darkened by this reagent, is much harder and paler in color, and could hardly be confused with the sulphide. The Fe-FeS eutectic structure has not been observed with the microscope, probably because (according to Wohrman) the components coagulate readily in the presence of excess iron.

The presence of carbon and manganese, as in commercial steels and cast iron, or of oxygen as in ingot iron, has of course an important influence on the equilibrium relations of iron and sulphur. These ternary alloys however are not included in the present discussion.

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¹Shown by C. R. Wohrman, in his: Inclusions in Iron, Trans., A.S.S.T., 1928, v. 14, p. 274.

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It is evident that our knowledge of this system is satisfactory only in the general outline, but that many details regarding the equilibrium relations in it are in need of further investigation. Indeed, the entire diagram should be redetermined with alloy specimens at least approaching modern standards of purity.

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Constitution of Iron-Tungsten Alloys

By W. P. Sykes*

The constitution diagram of the binary iron-tungsten system is given in Fig. 1. The data used in drawing this diagram were taken from reports of Honda and Murakami,¹ Sykes,^{2,3} Arnfelt,⁴ and Chartkoff and Sykes.⁴ As shown by the diagram, the system may be described as follows:

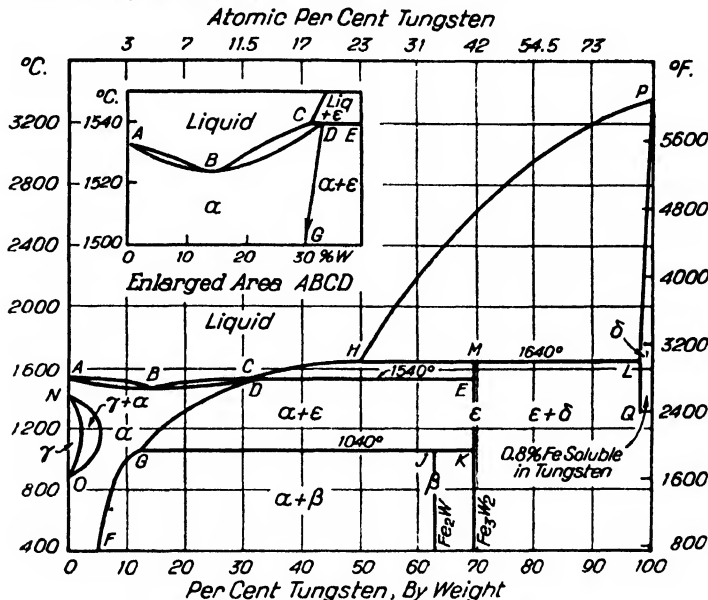


Fig. 1—Iron-Tungsten Constitution Diagram.

(a) With the addition of about 6% of tungsten the gamma form of iron is completely eliminated.

(b) The solidus and liquidus temperatures pass through a minimum of 1525°C. at a composition of about 15% tungsten.

(c) The alpha solid solution is formed at 1540°C. by a peritectic reaction between the iron-rich liquid and the solid epsilon phase (Fe_3W). At 1540°C. about 32% tungsten is dissolved in solid iron and the cube edge of the iron lattice has been increased about 1%. The solid solubility of tungsten in iron decreases to about 6% at 500°C.

(d) Upon heating to about 1640°C. the epsilon phase (Fe_3W) decomposes to form an iron-rich liquid and a tungsten-rich solid, delta. The latter dissolves about 0.8% iron with a slight contraction of the tungsten lattice.

(e) A second intermetallic phase, beta, corresponding to the formula Fe_2W (62% tungsten) was first identified by Arnfelt. This appears to be formed* by a peritectoid reaction at about 1040°C.

As shown in Fig. 2, the hardness of the iron-rich alloys increases continuously with the addition of tungsten up to about 50% tungsten. Compositions lying between 50 and 90% tungsten are rendered

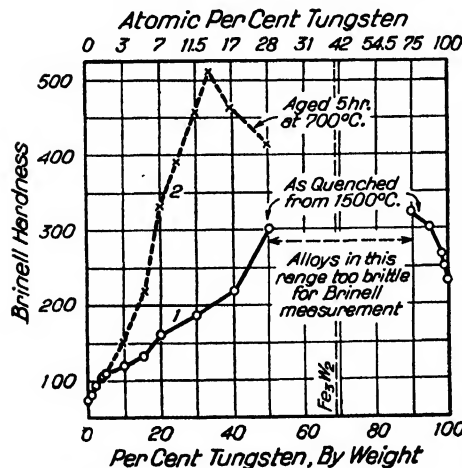


Fig. 2—Hardness of iron-tungsten alloys.

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especially brittle by the presence of a large amount of the intermetallic compound Fe_3W_2 .

The iron-rich solid solutions containing more than 10% tungsten are susceptible to precipitation hardening, as shown by curve 2 in Fig. 2. An alloy containing 30% tungsten when quenched from 1500°C. has a Brinell hardness of about 200 as a single phase solid solution. By reheating at 700°C. for a period of 5 hr. the Brinell number is increased to about 550.

The tensile strength of these alloys is increased by aging, as is the hardness. A decrease in ductility accompanies the increase in tensile strength.

Alloys containing as much as 20% tungsten can be forged, rolled, and drawn at temperatures from 700-800°C. As formed by sintering or casting, the iron-rich alloys containing more than 5% tungsten tend to have a coarse grain structure which can be eliminated only by mechanical working.

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Constitution of Iron-Vanadium Alloys

By Jerome Strauss*

In 1908 Vogel and Tammann² published the results of the first systematic study of the iron-vanadium system. They determined, however, only the liquidus and solidus lines, reporting no transformations in the solid state; part of this omission was obviously due to their failure to examine any alloys containing less than 10% vanadium. More recent investigations have not significantly altered the results reported at that date. By metallographic examination Oya³ confirmed findings that in the light of recent general investigation must obviously be correct, namely, that the isomorphous metals alpha iron and vanadium, being both of body-centered cubic structure, form a continuous series of solid solutions. Wever and Jellinghaus¹¹ studied the melting ranges of a series of alloys containing up to about 70% vanadium. With above 10% vanadium these alloys were not of high purity, containing 0.03-0.14% carbon and 0.16-2.01% silicon. At the same time the alloys of Vogel and Tammann were also not of high purity. Furthermore, the melting point of vanadium is not known with precision, having been placed variously between 1680 and 1750°C. The liquidus and solidus curves of Fig. 1 are therefore a compromise between the values on low vanadium alloys of Vogel and Tammann,² those on the purer alloys of Wever and Jellinghaus¹¹ and the melting point determination of most probable reliability, namely, the 1700°C. by Marden and Rich.⁷ The minimum solidification temperature is taken from Wever and Jellinghaus¹¹ at 31% vanadium and 1468°C., but the correct temperature may be slightly higher.

Putz¹ and Portevin⁴ both observed an increase in the temperature of the gamma to alpha transformation on the addition of vanadium to low carbon steels (0.1 and 0.2% carbon respectively) and Maurer who first proclaimed the existence of the "gamma loop" also used carbon-containing alloys, with 0.04-0.09%. All were correct in their deductions although not establishing the alpha-gamma boundary for pure alloys. There is still much disagreement concerning this boundary. The values for the extreme limit of the gamma phase ranges from 1.1-2.5% vanadium^{5, 6, 11, 14}. In view of the pro-

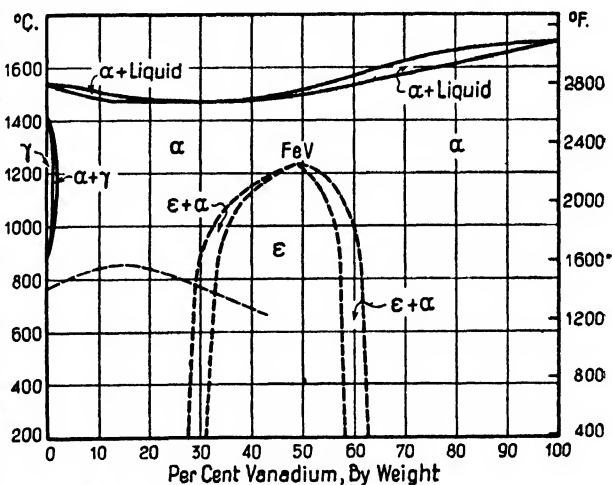


Fig. 1—Iron-Vanadium Constitution Diagram.

found effect of impurities, notably carbon, upon the outline of this field¹⁵ and the reported impurities of some investigations and obvious though unreported impurities of others¹, the limit of the gamma phase is here placed at 1.0% vanadium with the extreme of the adjacent gamma plus alpha field at 1.1%. This places maximum weight upon the work of Wever and Jellinghaus, whose low vanadium alloys contained as maximum impurities 0.01% carbon, 0.07% silicon, and 0.03% aluminum.

On the occurrence of the magnetic transformation there is also disagreement. Oya³ reported a slow increase in temperature with increased vanadium content, especially in the lower concentrations, with a maximum of about 850°C. at 15%;

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†Description of the nature, appearance, and method of preparation of some of the materials employed by some investigators leads the author to question some of the statements of purity which are not supported by detailed analyses; this applies especially to the vanadium used.

This article was not revised for this edition.

then a slow decrease changing to a rapid decrease above 20% and reaching room temperature at about 35% vanadium. Wever and Jellinghaus¹¹ reported a similar slow increase of the magnetic change up to 785°C. at 1.4% vanadium, then remaining at about this temperature (790°C. maximum) up to 29.5%; above this amount their conclusions require checking due to the presence of another phase associated with or replacing the solid solution. Their curve was similar to that of Oya but reached room temperature at 58% vanadium. Vogel and Martin¹⁴ showed a rise from 768°C. to about 820° at 3% vanadium and stated that the increase continued up to a content noted in different parts of their paper at 25 and 32%. Edlund¹⁶ noted values differing not too greatly from those of Wever and Jellinghaus up to about 25% vanadium, but a slower decrease above this percentage and no magnetic change above about 43%; the precision of the work was such that his data are used here.

As noted above, Wever and Jellinghaus described a new phase. Osawa and Oya¹² had observed that the change in the lattice parameter of the alloys did not proceed from that of iron (2.852Å) to that of vanadium (3.004Å) in accordance with Vegard's addition law. The later investigations confirmed these findings and, as a result of combined metallographic, thermal, X-ray, and magnetic data, outlined the field of what they assumed to be an intermetallic compound corresponding to the formula FeV and capable of dissolving limited amounts of either iron or vanadium; marginal two phase fields were also described. The separation of the pure compound was placed at 1234°C. and 48% vanadium (47.7 by formula). The lattice type was not definitely identified but stated to be complex. As there has been no published work in confirmation of the existence of this phase, its boundaries are indicated by dotted lines in the present diagram. The central field is here designated as epsilon since it is a solid solution and not a compound of constant composition.

It is apparent from this description that although parts of the iron-vanadium constitutional diagram are qualitatively correct, more work is required for precise location of the lines and definite confirmation of the intermetallic compound.

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Constitution of Iron-Carbon-Molybdenum Alloys*

The first attempt at complete determination of the iron-carbon-molybdenum system was made recently by Takesi Takei. This report represents a vast amount of experimental work. It is worthy of special note that this is probably the first time that the initial diagram of a ferrous ternary system is constructed in accordance with phase rule requirements. It is probable, then, that future contributions to this system will chiefly bring adjustments rather than effect radical changes.

In Fig. 1 is given the steel corner from the iron-carbon-molybdenum diagram. Although not given in Fig. 1, the phases in the complete diagram are identified as follows:

Phase	Explanation
α	Solution of Mo and C in α Fe
γ	Solution of Mo and C in γ Fe
c	Fe_3C (capable of dissolving Mo, C and Fe)
ω	Double carbide of Fe and Mo
ϵ	Fe_3Mo_2 containing Fe and C in solution
η	FeMo containing Fe and C in solution
θ	Mo_2C (capable of dissolving Fe and Mo)
δ	Solution of Fe and C in Mo
ν	The melt

Isothermal sections show the nature of the ternary system for the iron-carbon-molybdenum alloys. At 800°C. the diagram discloses the presence of the γ phase and at 1200°C. a liquid phase is present.

The complete diagram becomes speculative at high molybdenum and carbon concentrations. Fortunately, the portion which has already been established with reasonable certainty is also the portion of greatest usefulness—for low molybdenum contents.

Although isothermal sections alone do not tell what happens to alloys as they are heated or cooled, the trends of the various boundaries may be inferred from an inspection of the diagrams. The sec-

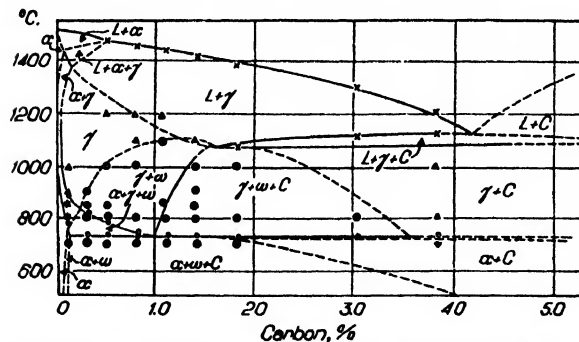


Fig. 2—Isothermal diagrams for iron-carbon-molybdenum alloys with 2% molybdenum.

Iron-Carbon-Molybdenum Alloys—Twelve structural diagrams for the iron-carbon-molybdenum system up to 1.2% carbon and 6.0% molybdenum were established from

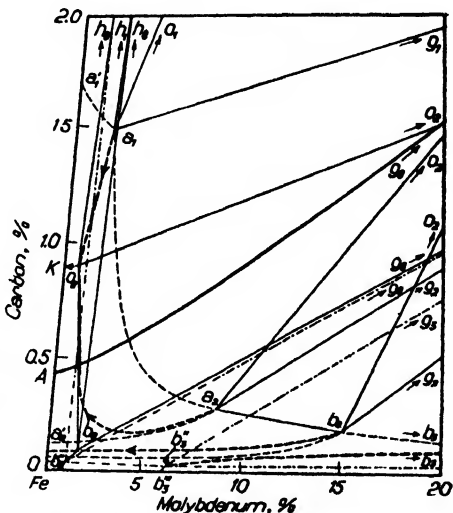


Fig. 1—Steel corner of the iron-carbon-molybdenum diagram.

tions of the diagram at 2, 4 and 10% molybdenum are shown in Fig. 2, 3 and 4. The complex nature of the system is caused principally by the appearance of the ω or double carbide phase. While these section diagrams of constant molybdenum content cannot be used to estimate relative proportions and compositions of phases present, they are useful in indicating the number and nature of phases present at any temperature and composition.

Structural Diagrams for
ams for the iron-carbon-
um were established from

*Abstracted from the literature by the editorial staff.

microscopic and hardness examinations of 41 alloys. The results of this study were reported in a paper by Blanchard, Parke and Herzog before the A.S.M., October, 1938, and published in the Transactions of the A.S.M. in 1939. The analysis range of the alloys used in this study follows: C 0.05-1.33%, Mo 0.04-6.34%, Mn 0.11-0.31%, Si 0.07-0.33%. All compositions were low in S and P.

Alloys were melted in a 30 lb. high frequency induction furnace. No aluminum additions were made. The ingots were forged into 1 in. round bars and ground to $\frac{1}{8}$ in. round. Specimens $1\frac{1}{2}$ in. long were held at temperature for 1 hr. Hardness measurements and microscopic observations were made at a point equidistant from the center and the surface of the specimen. In these diagrams the constituents are designated as follows:

C	Carbide
P	Pearlite
M	Martensite
ω	Double Carbide
W	Widmanstätten
B	Bainite
F	Ferrite

The diagrams in Fig. 5, 6, 7 and 8 show the structural compositions for alloys, water quenched from 1550 and 1650°F. and normalized at the same temperatures.

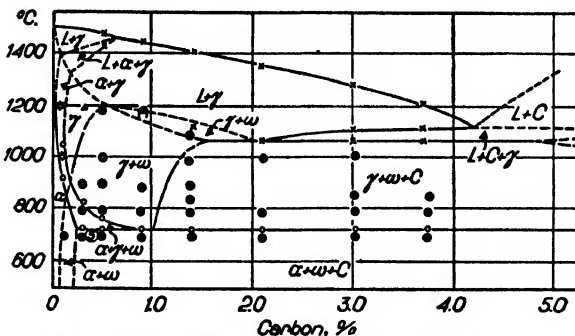


Fig. 3—Same as Fig. 2, but with 4% molybdenum.

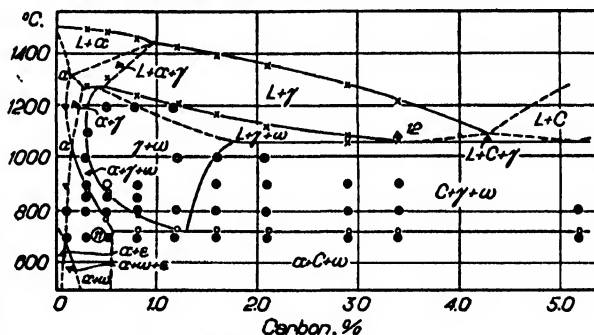


Fig. 4—Same as Fig. 2, but with 10% molybdenum.

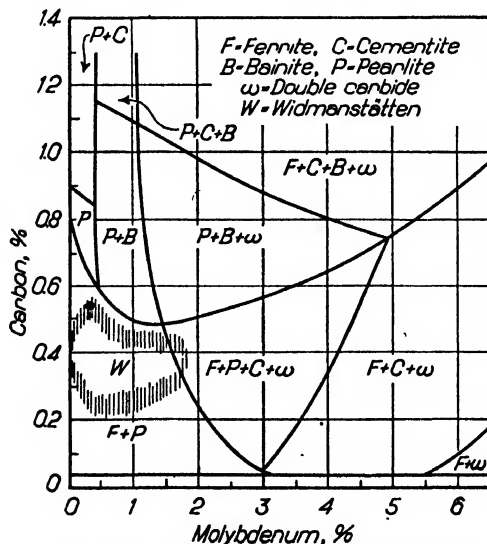


Fig. 5—Iron-carbon-molybdenum alloy air cooled from 1550°F.

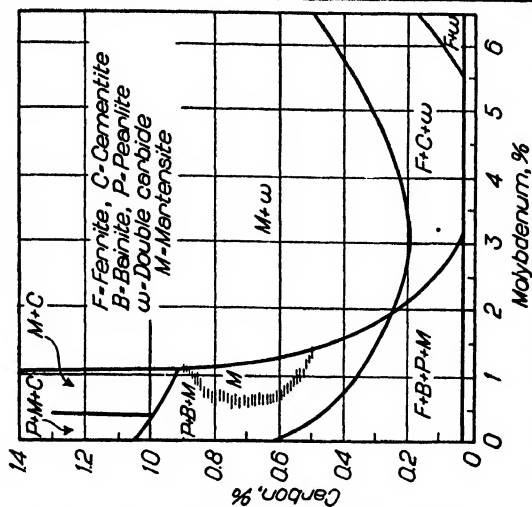


Fig. 6—Iron-carbon-molybdenum alloy quenched in water from 1650°F.

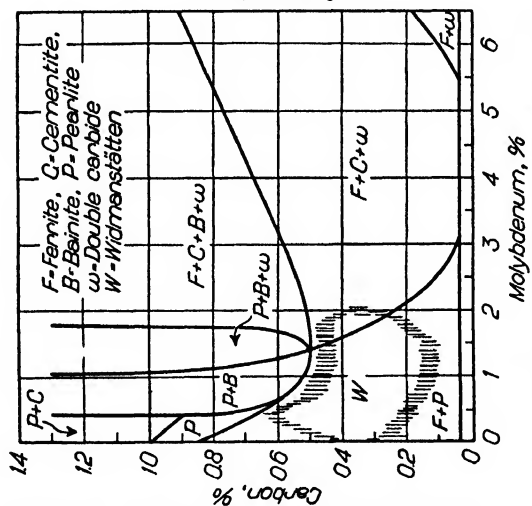


Fig. 7—Iron-carbon-molybdenum alloy air cooled from 1650°F.

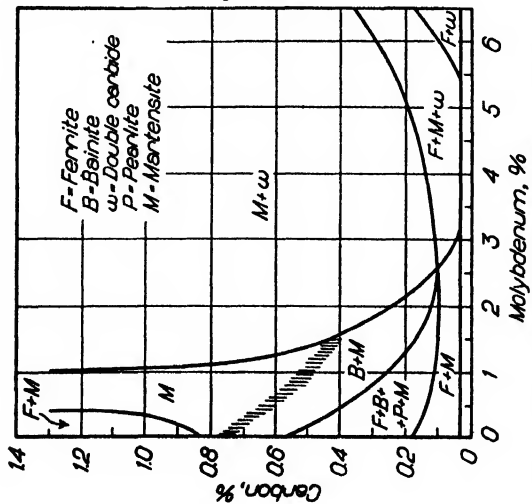


Fig. 8—Iron-carbon-molybdenum alloy quenched in water from 1650°F.

Constitution of Iron-Chromium-Carbon Alloys

By Walter Crafts*

Chromium-Carbon System—The chromium-carbon system has received attention since as early as 1856 when Sainte-Claire Deville investigated the reduction of chromium oxide by carbon. Since that time many investigations have been carried on for the purpose of establishing an equilibrium diagram for the system. A diagram was proposed by Hatsuta¹ and is probably the most accurate representation of equilibrium conditions available. The carbides Cr_7C_3 , Cr_3C_2 , Cr_7C_3 , are well established, but existence of CrC has not been verified. Recent work by Westgren² has shown that the carbide Cr_7C_3 is really Cr_{23}C_6 . The eutectic between chromium and Cr_7C_3 is placed at 1485°C . and 3.7% carbon.

According to X-ray analysis the carbide Cr_7C_3 is face-centered cubic, Cr_3C_2 is trigonal and Cr_7C_3 is orthorhombic. With reference to the ternary system iron-chromium-carbon, only Cr_7C_3 and Cr_3C_2 need be considered, since Cr_7C_3 does not occur in any of the usual alloys.

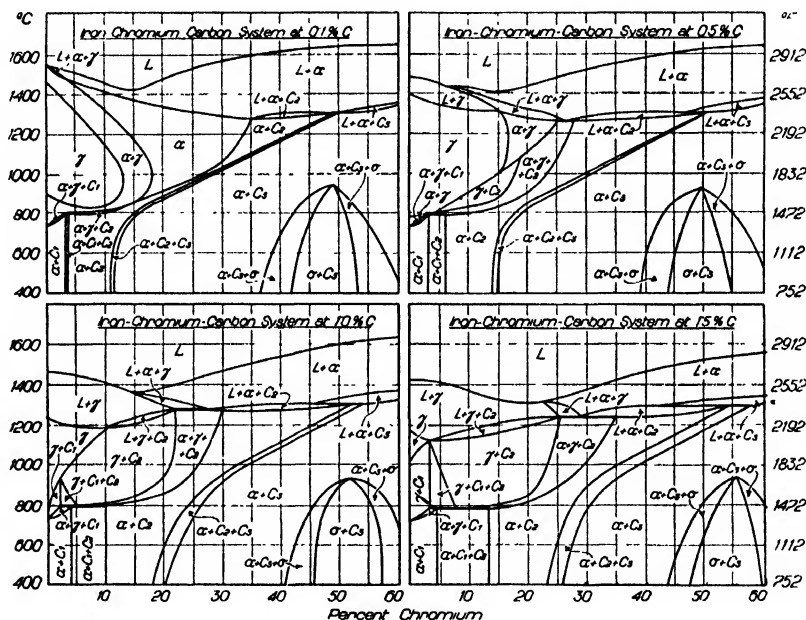


Fig. 1.—Iron-chromium-carbon system at 0.10, 0.5, 1.0, and 1.5% carbon.

Iron-Chromium-Carbon System—The system iron-chromium-carbon has been studied by many investigators, and sufficient data have been obtained to justify the construction of a ternary diagram for the iron-rich corner of the system. While some details of the contiguous binary systems are not certain, the general features of the partial system iron, iron-carbide, chromium-carbide, chromium are so well recognized that the diagrams taken chiefly from the investigations by Tofaute, Sponheuer, and Bennek³ and Tofaute, Küttner, and Büttinghaus⁴ may be considered satisfactory for practical interpretation of the behavior of the usual iron-chromium-carbon alloys.

Sections at 0.1, 0.5, 1.0, and 1.5% carbon are given in Fig. 1. Fig. 2 shows the sections at constant chromium contents of 5, 12, 20, and 30%. An isothermal section of the iron-chromium-carbon diagram⁵ at temperatures of 1150°C . is given in Fig. 3.

The carbide phases designated as C_1 , C_2 , and C_3 in the diagrams have the following formulae and compositions:

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C_1 — $(Fe,Cr)_3C$ —Iron carbide capable of dissolving up to about 15% chromium.
 C_2 — $(Cr,Fe)_7C_3$ —Chromium carbide capable of dissolving up to about 55% iron.
 C_3 — $(Cr,Fe)_4C$ —Chromium carbide capable of dissolving up to about 25% iron.

The other phases have been designated as follows:

L—Liquid
 X—Ferrite
 γ —Austenite
 σ —Sigma ($FeCr$)

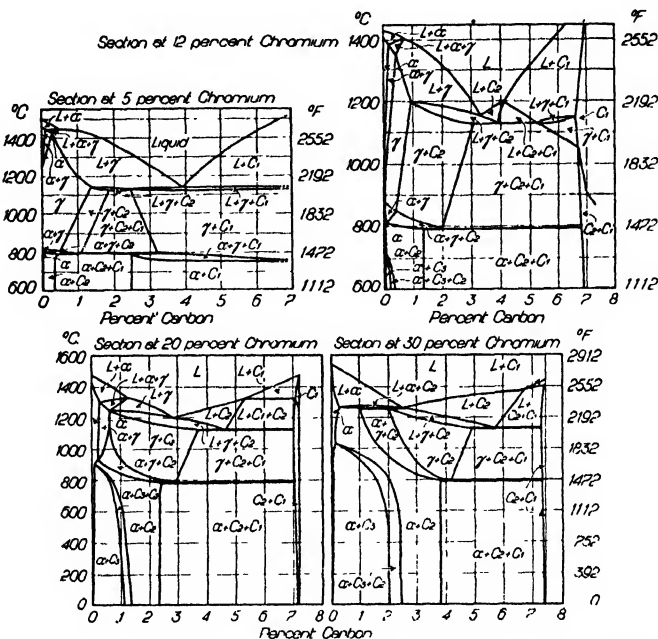


Fig. 2—Iron-chromium-carbon system at 5, 12, 20, and 30% chromium.

The orthorhombic carbide $(Fe,Cr)_3C$ is found in only the lowest chromium steels, and as the chromium content is increased the trigonal carbide $(Cr,Fe)_7C_3$ makes its appearance. The presence of cubic carbide Cr_3C is dependent upon both the carbon and chromium contents. For example in low carbon steels it appears at about 10% chromium whereas with 3% carbon present it is found only in alloys containing more than about 35% chromium. It is fairly certain that $(Cr,Fe)_7C_3$ forms as a result of peritectic transformation, and the same is probably true of $(Cr,Fe)_3C$.

Four 4-phase equilibria exist in the iron-chromium-carbon system. Three of these are of the transition-plane type while the other is of the eutectic type. The ternary eutectic point lies close to the plane of the iron-carbon diagram. The nonvariant equilibrium of greatest practical importance is the one involving the phases alpha, gamma, $(Fe,Cr)_3C$ and $(Cr,Fe)_7C_3$, which exists at about 800°C. In view of the position of the co-ordinates for this quadrangle, namely 2.6% chromium and 0.05% carbon for the alpha corner and 2%

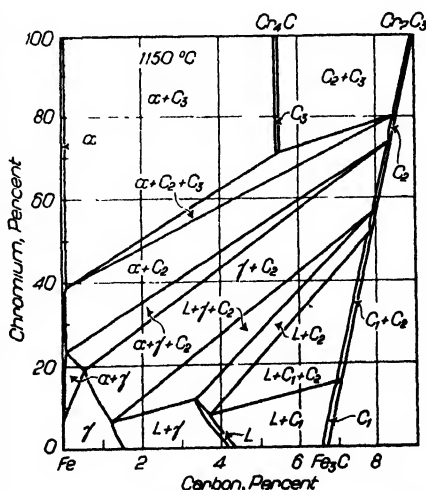


Fig. 3—Iron-chromium-carbon system at 1150°C.

which exists at about 800°C. In view of the position of the co-ordinates for this quadrangle, namely 2.6% chromium and 0.05% carbon for the alpha corner and 2%

chromium and 0.7% carbon for the gamma corner, it is possible for the chromium carbide, Cr_7C_3 , to appear in many steels containing more than 2% chromium.

The constitution of the alloys with less than about 2% chromium is not markedly different from that of iron-carbon alloys. With increasing chromium content, however, the single phase gamma region is shifted to lower carbon contents and disappears entirely at about 20% chromium. The temperature limits of the region are also restricted with increased chromium content. From a practical standpoint this means that higher heat treating temperatures must be used for those operations that depend upon transformation to and from the gamma phase.

The solubility of carbon in the alpha phase of iron-rich alloys at temperatures just below the freezing point increases slightly with increasing chromium content. The carbon content of the "eutectoid" is decreased by increasing the chromium content.

At chromium contents above about 40% it will be noted that the phase designated as "sigma" makes its appearance. It appears likely that this phase results from the allotropic transformation of a saturated alpha solid solution although it has been classed as a compound and assigned the formula FeCr . This phase is not stable at temperatures above 900°C . and in most cases is developed only after extended holding times in the temperature range of 600 - 1000°C .

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Constitution of Iron-Manganese-Carbon Alloys

By C. Wells*

Historical—The iron-manganese-carbon diagram derived by Bain, Davenport, and Waring,¹ published in 1932, was the first to give reasonably complete data concerning the constitution of the industrially important ternary alloys in the solid state when brought approximately to equilibrium at various temperatures.

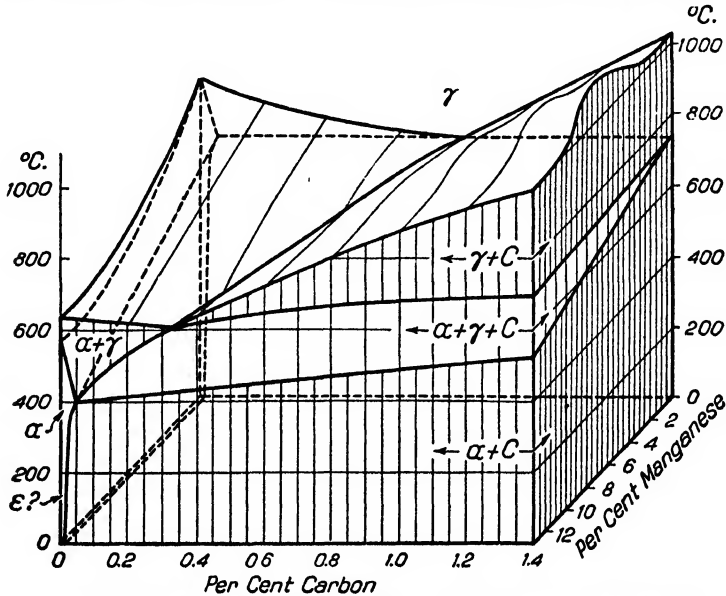


Fig. 1—A diagrammatic representation of the iron-manganese-carbon ternary diagram.

Between 1888, when Hadfield steel was discovered, and 1932 a number of investigations were conducted using various experimental methods for the purpose of determining the effect of heat treatments on the constitution of the ternary alloys

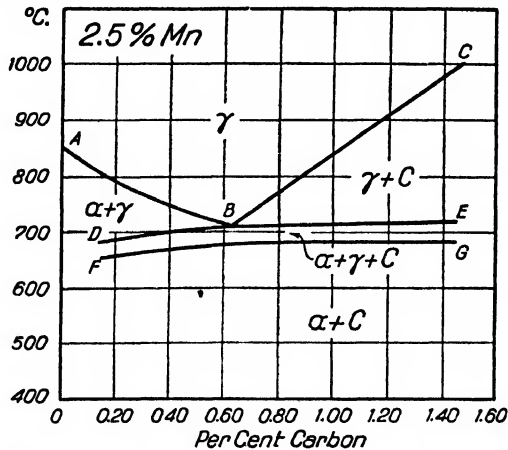


Fig. 2—2.5% manganese section of the ternary diagram for alloys of iron, manganese, and carbon.

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of commercial purity.³ In general, however, this effort was concentrated on the high and low manganese steels of industrial importance, and the supposedly brittle alloys of intermediate manganese content were neglected. Furthermore, in only

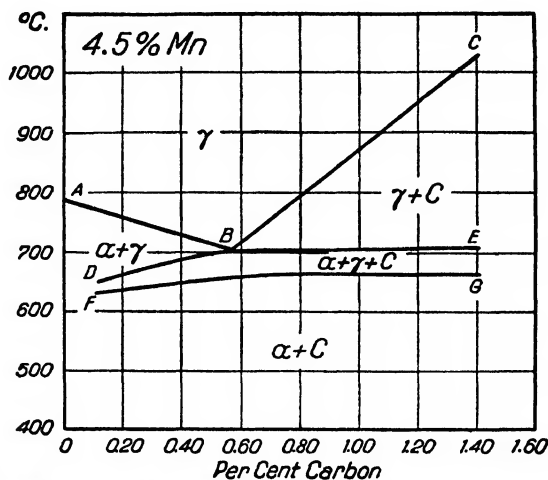


Fig. 3—4.5% manganese section of the ternary diagram for alloys of iron, manganese, and carbon.

one or two of these investigations were the heat treatments prolonged sufficiently to bring the high manganese ternary alloys close to equilibrium. It is not surprising, therefore, that the rather uncertain diagram published by Guillet,⁴ showing

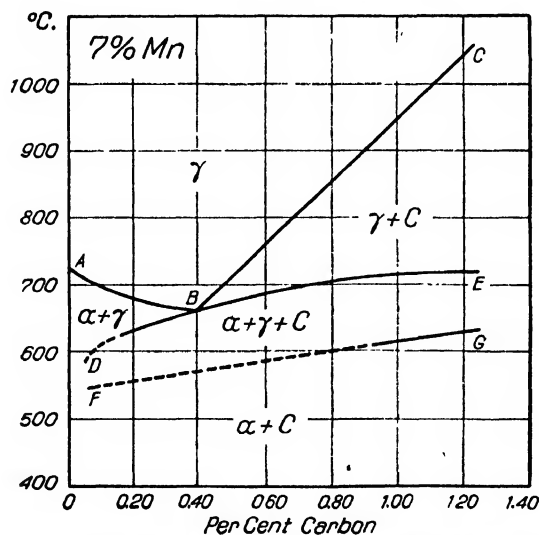


Fig. 4—7% manganese section of the ternary diagram for alloys of iron, manganese, and carbon.

simply the constitution of iron-manganese-carbon alloys after being forged and air cooled to room temperature, was the best available until the paper of Bain, Davenport, and Waring was published.

Although the diagram of Bain and his co-workers may not be considered en-

tirely satisfactory, because commercial rather than high purity alloys were used, this objection from a practical standpoint is not serious, since the broad aspects

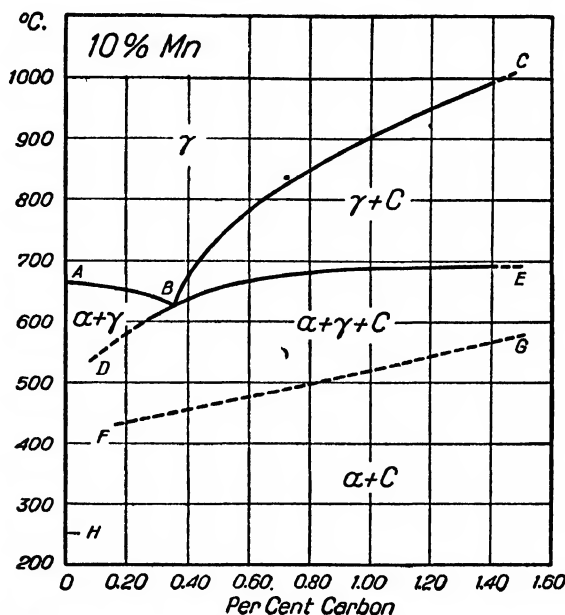


Fig. 5—10% manganese section of the ternary diagram for alloys of iron, manganese, and carbon.

of the constitutional diagram have since been shown to remain the same. This is clear from a series of papers^{4, 5, 6}, which describe the constitution in the solid state

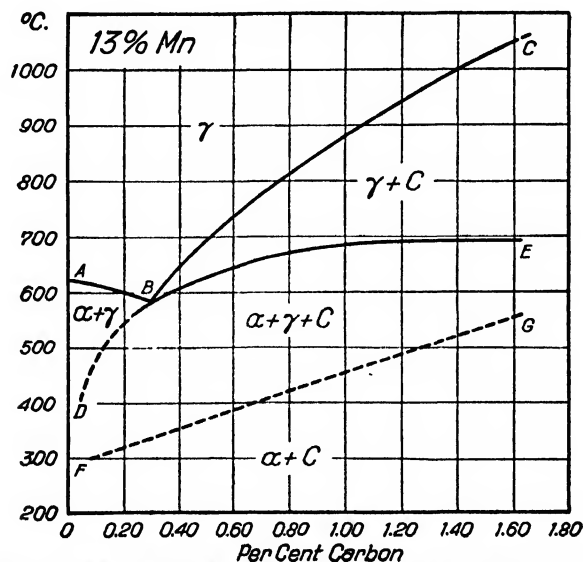


Fig. 6—13% manganese section of the ternary diagram for alloys of iron, manganese, and carbon.

of high purity iron-manganese-carbon alloys containing up to about 13% manganese and 1.5% carbon.

Iron-Manganese-Carbon Constitution Diagram—The diagrams published by E. C. Bain and co-authors and by F. M. Walters and co-authors were determined by examination under the microscope of quenched specimens, previously brought close to equilibrium at crucial temperatures. In the determination of the 2.5 and 4.5% manganese sections of the ternary diagram dilatometric studies also proved useful.

A comparison of the results using alloys of commercial purity with those

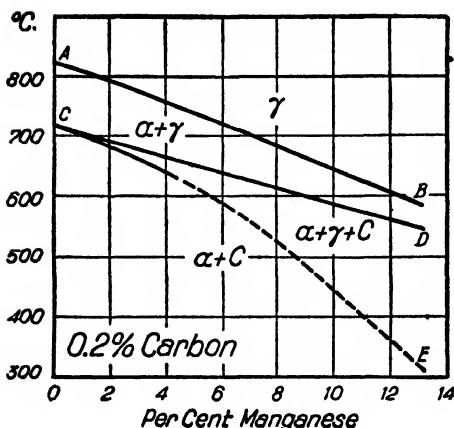


Fig. 7—0.2% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

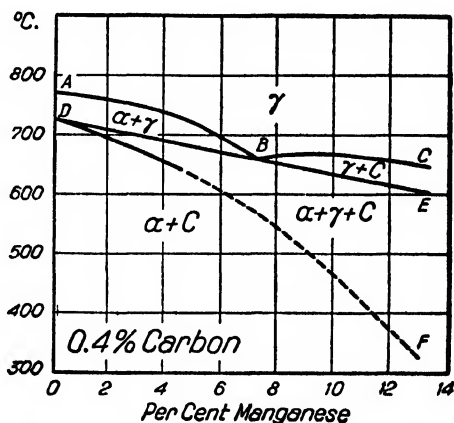


Fig. 8—0.4% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

obtained using high purity alloys shows general agreement. For the purpose of a general understanding of the behavior of the ternary alloys as a whole, a diagrammatic representation of the ternary diagram is given in Fig. 1. The space indicated by ϵ ? is of doubtful significance because it is not known whether epsilon is a stable or transition constituent. At temperatures just above those indicated by the upper

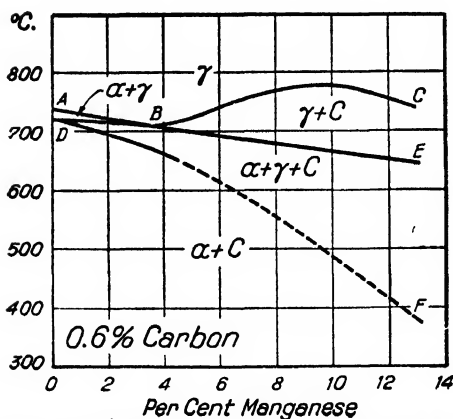


Fig. 9—0.6% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

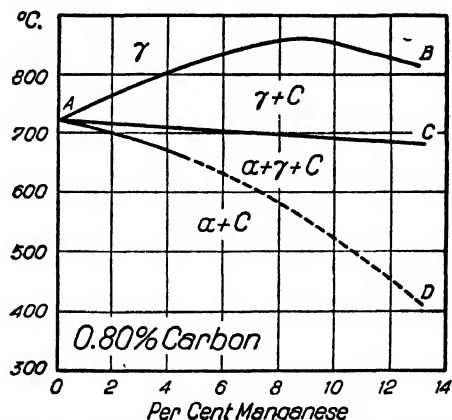


Fig. 10—0.8% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

surfaces only the gamma phase is stable. Below these the stable phases are as represented and occur between limits indicated by the limiting boundaries. The line between the upper two surfaces represents the upper eutectoid compositions and temperatures (723°C. and 0.80% carbon for pure iron-carbon alloys, and 600°C. and 0.30% carbon for 13% manganese ternary alloys). As alloys of suitable composi-

tions are cooled at an extremely slow rate from the gamma field (above ABC, Figs. 2-6) proeutectoid carbide separates between temperature limits indicated by CBE and proeutectoid alpha solid solution between limits indicated by ABD. Cooling further (below DBE) at a similarly slow rate results in a simultaneous precipita-

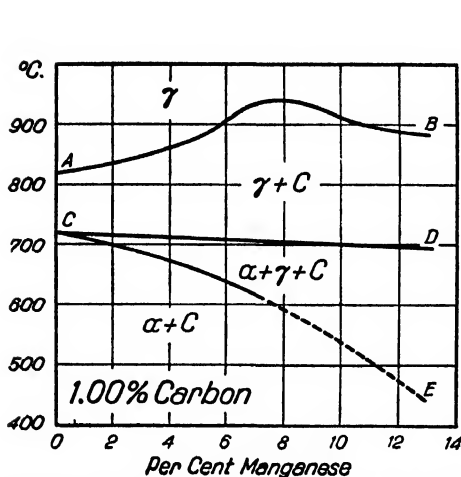


Fig. 11—1.0% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

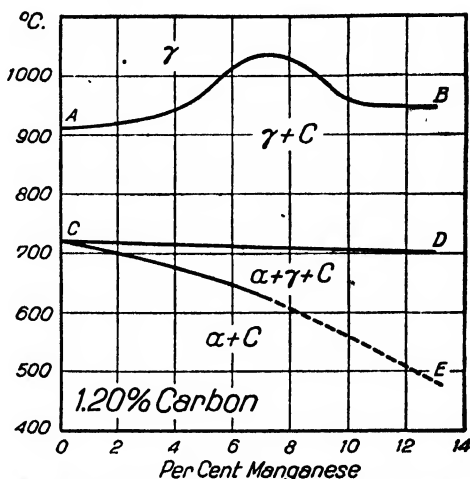


Fig. 12—1.2% carbon section of the ternary diagram for alloys of iron, manganese, and carbon.

tion of alpha solid solution and carbide from the gamma solid solution giving a binary eutectoid of varying composition as the temperature is lowered, until temperatures represented by FG are reached, at which point the remaining gamma solid solution in the alloys is completely transformed into alpha solid solution + carbide.

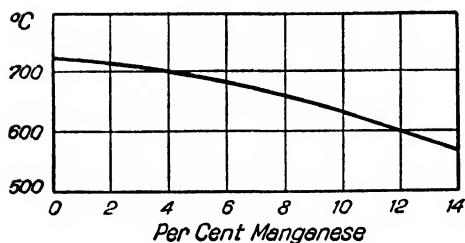


Fig. 13—Curve showing the influence of manganese on the upper eutectoid temperature limit in alloys of eutectoid composition.

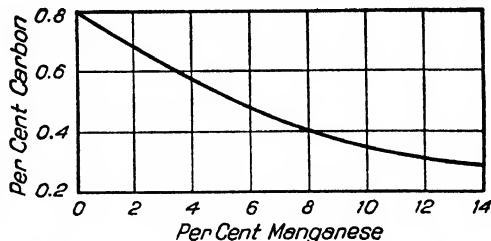


Fig. 14—Curve showing the influence of manganese on the carbon concentration in alloys of eutectoid composition.

Adding manganese to iron-carbon alloys makes possible the co-existence of three phases, alpha, gamma, and carbide, in equilibrium (field between DE and FG, Figs. 2-6).† As carbon is added to iron-manganese alloys of constant manganese content, the upper and lower temperature limits at which the three phases can exist in equilibrium are raised.*

†A discussion of the conditions which may give rise to the type of sectional diagram indicated in Figs. 2-6 is given in "Principles of Phase Diagrams," by J. S. Marsh¹², p. 134-146.

*When the carbide, gamma, and alpha phases co-exist in equilibrium, the components, carbon, manganese, and iron are so distributed that the concentration of the manganese and of the carbon is highest in the carbide, intermediate in the gamma, and lowest in the alpha phases. Due to this distribution of components in the phases, an increase in carbon in iron-manganese-carbon alloys of constant manganese content results in a decrease of manganese in the gamma in equilibrium with alpha and carbide phases at the upper and lower temperature limits of the eutectoid reaction and therefore in a raising of the upper and lower temperature limits of the three-phase zone.

The effect of manganese upon the temperature zones of stability for the phases in alloys of constant carbon content is indicated in Fig. 7-12.

The upper temperature limit of the eutectoid reaction as indicated by B (Fig. 2-6) is lowered with an increase of manganese in the ternary alloys (Fig. 13), and the carbon concentration in these ternary alloys of eutectoid composition is also lowered with increase of manganese (Fig. 14).

Bain and co-authors have indicated a small single alpha phase field in their sectional diagrams; but Walters and co-authors have preferred not to do this, because there are insufficient equilibrium data available to indicate the limits of this field with certainty. The single alpha phase field if indicated in the sectional diagrams (Fig. 2-6) would appear to the left of and above DF.

An epsilon phase field is not indicated in any of the diagrams, because there is much uncertainty regarding the stability* of epsilon, and because the knowledge of the phase relationships between epsilon and other phases is uncertain.

Since the sectional diagrams presented are neither binary nor pseudobinary diagrams, they give no indication of the proportions or compositions of two or more phases co-existing in equilibrium. Until such time that the chemical compositions of each phase in equilibrium with the other phases are known, only an incomplete knowledge of the portion of the ternary diagram studied is possible. At the present time little data of this kind are available.

Phases Present—Up to 13% manganese and 1.5% carbon no phases crystallographically different from those found in the binary iron-manganese and iron-carbon alloys have been observed.

Carbide—Iron-manganese carbide, (Fe, Mn)₃C, which occurs in the ternary alloys containing up to 13% manganese and 1.5% carbon has an orthorhombic structure⁸ similar to that of cementite in iron-carbon alloys, and contains about the same concentration of carbon as iron carbide. The concentration of manganese in the carbide occurring in these ternary alloys depends upon the concentration of manganese in the alloys.¹⁰ Under equilibrium conditions the percentage of manganese in the carbide is always much higher than that in the alloy, and in high manganese steels of the Hadfield type the carbide present may contain between 20 and 25% manganese, in which case there would be 1 atom of manganese to every 3 or 4 atoms of iron in the carbide. The analysis of carbide separated from alloys containing 1% carbon and 5-13% manganese is given by Arnold and Read¹¹ as approximately 7% carbon and 22% manganese (iron by difference). In ternary alloys of much higher manganese content other carbides (Mn, Fe)₃C, (Mn, Fe)₂C₃, and (Mn, Fe)₂C₅ may exist. This is evident from a comparison of the data of Westgren and Phragmén¹⁴ with those of Holmquist¹⁵ and Wells¹⁶ which show that the carbides of manganese (probably Mn₃C and Mn₂C₃) are very similar to those of chromium (Cr₃C and Cr₂C₃) in structure and dimensions.

Gamma Iron-Manganese-Carbon Solid Solution—In the gamma phase manganese atoms replace some of the iron atoms at the lattice points of the face-centered cubic gamma iron lattice while carbon atoms enter the interstices¹¹. Both manganese and carbon in solution in gamma iron increase the size of the unit cell.

Alpha Phase—This is an iron-manganese solid solution in which the solubility of carbon is quite low.¹² In this phase manganese atoms replace some of the iron atoms in the body-centered cubic alpha iron lattice and cause an increase in the size of the unit cell.

Epsilon Constituent—This constituent has a close-packed hexagonal crystal structure and occurs most readily in iron-manganese-carbon alloys containing high manganese and low carbon concentrations. The formation of epsilon in iron-manganese alloys containing very low carbon concentrations is described in this handbook. See chapter on "Constitution of Iron-Manganese Alloys."

Epsilon also forms from the gamma phase in high manganese steels of the Hadfield type during cooling after a heat treatment to precipitate most of the carbide from the gamma phase.

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*Bain believes epsilon may be a transition phase; Ishiwara⁷ that it is an intermetallic compound formed by a peritectoid reaction; and Sisco and Marsh⁸ that epsilon may be unstable at atmospheric pressure but stable at high pressure.

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The Constitution of Iron-Nickel-Aluminum Alloys

By L. L. Wyman*

The iron-nickel-aluminum ternary system has only been partially explored, the work on this being done by Köster,¹ and more recently by Bradley and Taylor.² The room temperature plots of these two diagrams do not entirely conform to the best available information on the three binary systems involved, and need some modification in order to do so.

The Köster diagram consists essentially of the ranges of the alpha (Bcc) and gamma (Fcc) alloys, established by thermal, microscopic, and magnetic analyses.

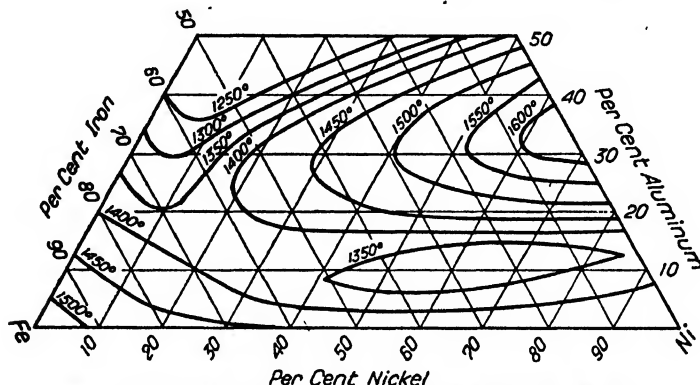


Fig. 1—Liquidus surface of the iron-nickel-aluminum system.

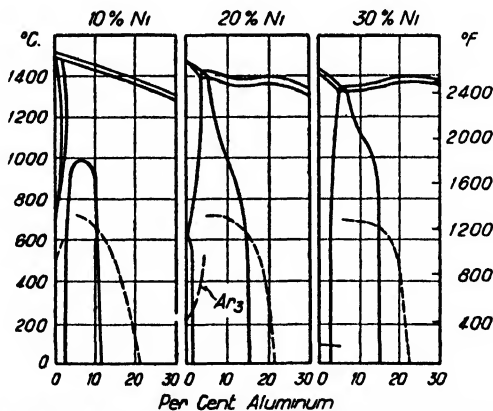


Fig. 2—Elevations at various nickel contents in the iron corner of the iron-nickel-aluminum system.

The Bradley and Taylor diagram, while it incorporates essentially the same "two phase" area, shows that this range is made more complex by the formation of superlattices.

The work of other investigators has shown that the magnetic properties are related to the formation of superlattices rather than to the phase relationships, so that the Bradley and Taylor diagram, taken as confirmation of the Köster ternary, and the best knowledge of the binary systems, might be considered the nearest to the true construction which is known at present.

Fig. 1 shows the plot of the liquidus surface of the ternary system, as worked out by Köster, while Fig. 2 shows the elevation at various nickel contents, in the iron corner of the ternary system (Köster).

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Fig. 3 shows the room temperature plot of the ternary system constructed according to the best information, using the phase and magnetic limits established by Köster, and the superlattice fields according to Bradley and Taylor, having both conform to the most reliable binary systems as limits.

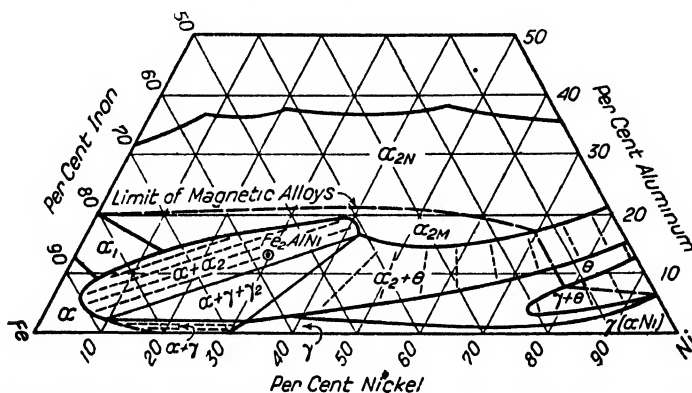


Fig. 3—Room temperature arrangement of the iron-nickel-aluminum system.

The nomenclature used is in conformity with the iron structures, alpha being body-centered cubic, and gamma being face-centered cubic.

Beginning in the iron-rich corner of the diagram it will be noted that the alpha Fe-Al alloys have two superstructures, the α_1 being of the Fe_3Al type, having iron atoms at the cube corners and iron and aluminum atoms alternating in the center positions in adjacent cubes, while the α_2 has the FeAl type of superlattice with iron atoms at the cube corners and aluminum atoms at the cube centers.

The shading lines in the alpha and gamma, alpha and α_2 , and theta, gamma and theta fields are in accordance with the Bradley and Taylor diagrams and are intended to show that the products of decomposition of any alloy having a composition represented as a point on these or similar lines would be represented by the phases corresponding to where these lines intersect the adjacent fields.

The nickel-rich ternary alloys have not been clearly established as yet, for Bradley and Taylor believe that the nickel-rich Al-Ni solid solution has a superlattice, while Alexander and Vaughan³ clearly reveal the presence of a new face-centered phase theta. Consequently this portion of the diagram does not conform to equilibrium relationships.

The interesting alloys in this system are the permanent magnet materials in the neighborhood of the compound Fe_2NiAl (29.7% Ni, 13.7% Al) which on proper cooling set up a superlattice, and give rise to remarkable magnetic properties.

The slow cooling of Fe_2NiAl places it in a two phase field made up of alpha, having its atoms at random, and the α_2 phase having a superlattice. The former also has a lattice spacing 0.3% less than the latter. Cooling the alloys in this range at the proper rate permits a portion of the above reaction to take place, but does not carry on to completion. This gives rise to a condition of immense strain, due to the differences in lattice size, to which Bradley and Taylor² attribute the high coercivity of these compositions.

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The Iron-Nickel-Chromium System

By Edgar C. Bain* and Robert H. Aborn†

The ternary system iron-nickel-chromium is particularly interesting from the scientific standpoint in that it is relatively simple, and at the same time carries the reflection of phase shifts accompanying allotropy in one of its components, iron.

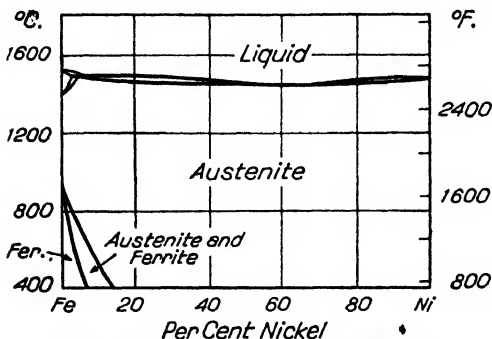


Fig. 1—Iron-Nickel Constitution Diagram.

At the outset it is obvious that iron, in one or the other of its allotropic states, forms a complete series of solid solutions with chromium and also with nickel. Thus ferrite, the alpha or delta iron solid solution, may carry only limited

amounts of nickel, but approach 100% chromium without any new phase appearing. Similarly austenite, the gamma iron solid solution, may carry only limited chromium, but approach 100% nickel. Thus, except for intermetallic compounds (and one does exist below about 1650°F.), the entire system must consist only of two phases (body- and face-centered cubic) which, however, will vary considerably as to composition range depending upon temperature. In spite of the fact that the words austenite and ferrite are usually applied only to relatively dilute solid solutions in the two forms of iron, it is nevertheless so convenient to extend the terms for the present

consideration, to higher concentrations of dissolved elements that this procedure will be adopted.

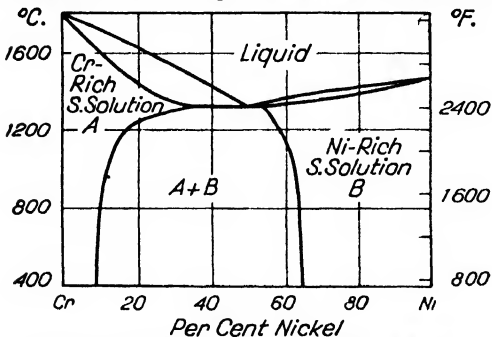


Fig. 3—Chromium-Nickel Constitution Diagram.

While there is little evidence that the chromium-rich ternary alloys have been explored, there is nevertheless a fair degree of probability that the phases at equilibrium in the entire system may be predicted now with considerable assurance; the character of the system in the iron or nickel-rich range permits of some reasonably valid inferences concerning the remainder of the system. Before the several phases in the three component alloys are considered it may be well to review the three binary equilibrium diagrams, Fe-Ni, Fe-Cr and Cr-Ni, as set forth in Fig. 1, 2 and 3.

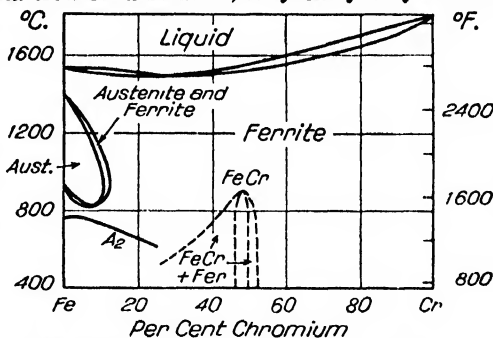


Fig. 2—Iron-Chromium Constitution Diagram.

From various sources, a fairly accurate approximation of the melting temperatures of the binary systems have been assembled; with reference to the ternary alloys little is known, but commercial melting experience shows that the customary iron-chromium-nickel alloys melt at temperatures not much below the fusion temperatures of the binaries, especially in the iron-rich compositions. From this it may be inferred that in the three-dimensional phase diagram the solidus-

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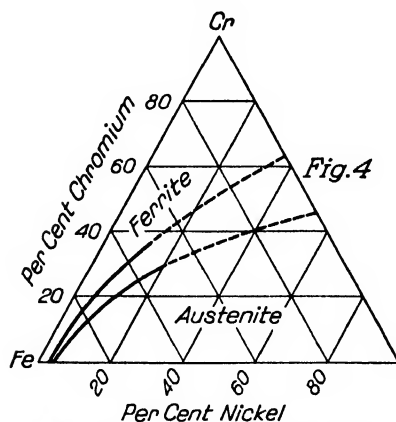


Fig. 4—Phase distribution in the iron-nickel-chromium system at temperatures near incipient fusion.

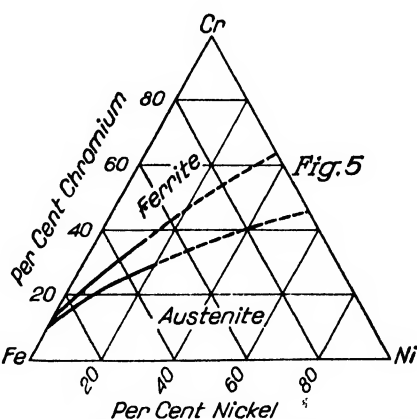


Fig. 5—Phase distribution in the iron-nickel-chromium system at temperatures (varying with composition) corresponding to maximum composition range for austenite.

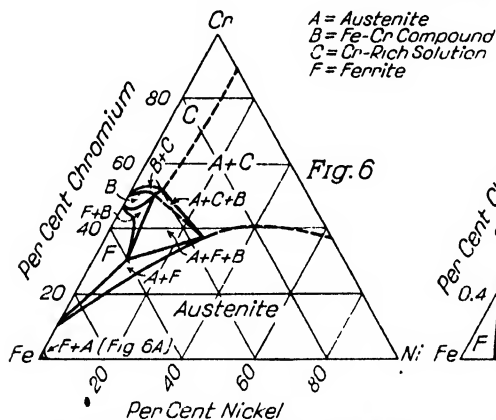


Fig. 6—Phase distribution of the iron-nickel-chromium system at about 900°C. (1650°F.).

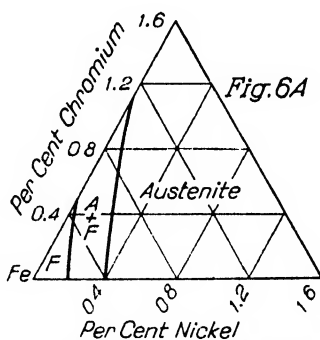


Fig. 6A—An enlarged view of the iron-rich corner of Fig. 6.

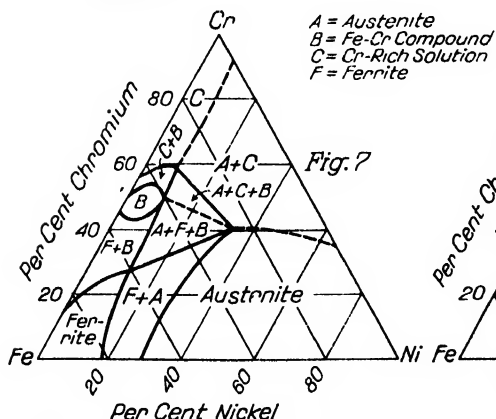


Fig. 7—Probable phase distribution in the iron-nickel-chromium system at about 870°F.

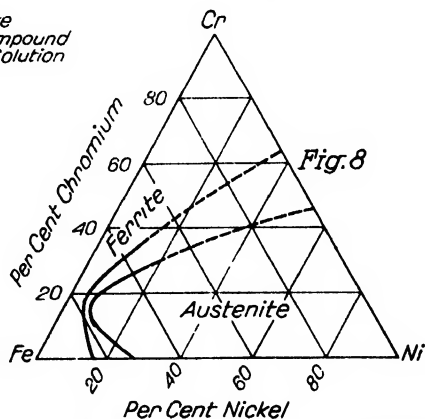


Fig. 8—Constitution of the iron-nickel-chromium system as developed by rapid cooling from the conditions of Fig. 5.

liquidus surfaces are fairly flat. With respect to the conditions in the solid state the knowledge is more abundant.

Fig. 4† shows the state of affairs as regards the constituent phases just below the solidification range. The high temperature alpha iron (delta iron) solid solutions make themselves felt by a strong sweep of the ferritic crystal structure into the iron-

nickel side of the diagram. Fig. 4 may be regarded as a plan view of the ternary diagram with the two phase (solid and liquid) regions removed.

As the temperature is lowered the distribution of phases is considerably altered, until within the temperature range approximately 1650-2370°F. (the exact temperature depending upon the composition) the gamma iron solid solution reaches its maximum extent, and, correspondingly, the purely ferritic family of alloys is reduced to its minimum extent. This is illustrated in

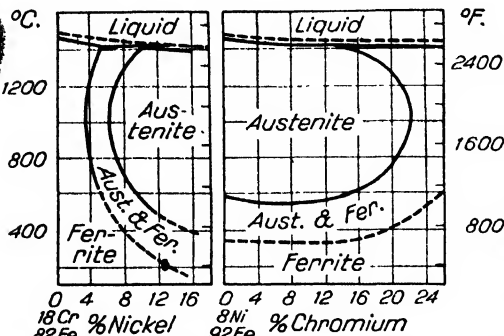


Fig. 9.—The effect upon constitution of (left) nickel in an 18% chromium alloy, and of chromium (right) upon an 8% nickel alloy.

Fig. 5. A plane section through the (solid) ternary constitution diagram at the 1650°F. temperature level is shown in Fig. 6. The iron-chromium compound (probably Fe-Cr) first appears at this level and thereby introduces some six new phase fields, owing to its binary and ternary equilibria with ferrite, austenite, and chromium-rich solid solution. A curious feature of the iron-rich corner is shown in enlarged detail in Fig. 6A. This is occasioned by the fact that the A_s transformation in purified iron is in the vicinity of 1670°F. and that small additions of either nickel or chromium then tend to stabilize austenite and thereby lower the A_s transformation to temperatures below 1650°F.

The compound, based upon the approximate composition Fe-Cr, forms only from compositions which are, at least in part, ferritic, and then relatively slowly, so that in rapidly cooled alloys it is never found. Its rate of formation is at a maximum only a few degrees below the maximum temperature at which it may exist at equilibrium.* The approximate iron-chromium composition range in which it may form is illustrated in Fig. 2, but it may form also in alloys carrying as much as approximately 30% nickel. (See Fig. 6 and 7). Apparently it may not form from ferrite richer in chromium than about 55%. Nickel slightly raises the maximum temperature of stability of the compound so that in the solid diagram its phase boundary is seemingly a mound rising to somewhat above 1650°F. at some 5% nickel and slightly under 50% chromium.

The compound itself is hard and brittle and nonmagnetic; its crystal structure has not been reported and the diffraction pattern is such as to suggest a complex crystal of low symmetry. When it is formed in an iron alloy of some 30% chromium after long periods at about 900°F. it is located in a thin intergranular

†The usual triangular portrayal of phase distribution at constant temperature for three components is employed here not only for single temperatures but also for certain qualified conditions over a temperature range. It should be borne in mind that only two independent variables are really possible of representation on a plane surface and that three component systems are really of such a nature since the concentration of any one component of the three is a function of the sum of the concentrations of the other two; that is, $100\% - A\% - B\% = C\%$. The triangle merely cuts off the unreal magnitudes of any two components at the 100% maximum.

It should be noted that all diagrams shown here are only approximate but they are drawn in such a way as to be consistent both with the available information and with thermodynamic considerations as expressed in the phase rule.

*It is, of course, nearly impossible to prove that the compound, based on FeCr would form in absolutely pure iron-chromium alloys, with or without nickel. Adcock is inclined toward the interpretation that the compound forms as a result of possible contamination. The present authors on the other hand believe that the large number of instances in which the compound has been observed warrants including it in the equilibrium system. One of them found this constituent formed throughout the whole of a 1 in. section of iron-chromium alloy prepared by melting pure electrolytic metals in vacuum and subsequently maintaining the metal at the most rapid transformation temperature, also in vacuum. It is suggested that Adcock use a temperature too low to develop the transformation in the compositions employed to an extent sufficient for detection.

network and extreme brittleness results. Some brittleness or loss of ductility appears in such compositions, however, before evidence of any precipitation of the compound exists.

At temperatures much below about 1290°F. the alloys carrying more than 15% nickel, or even less nickel if accompanied by perhaps 10% chromium, are unable to reach the equilibrium state in any ordinary time interval; instead they tend to

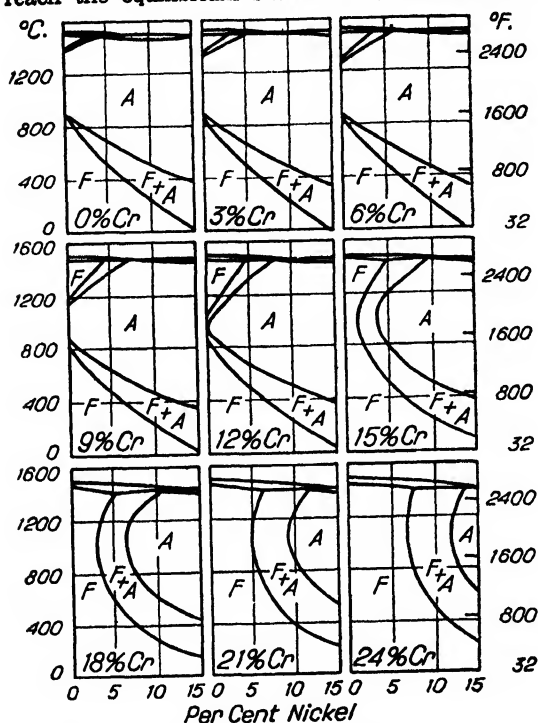


Fig. 10—The effect of nickel upon the constitution of various alloys of constant chromium content. (Constant chromium sections of the Solid Three Dimensional Ternary Diagram, temperature vertical).

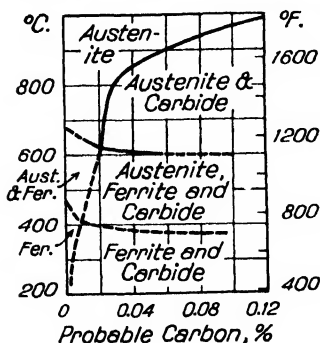


Fig. 11—Probable Equilibrium Diagram of the 18 chromium-8 nickel alloys of various carbon contents.

preserve the constitution set up at some higher temperature during a previous heating. This means, in general, that the alloys are more austenitic at room temperature than corresponds to the true equilibrium at that temperature. As a result, special time consuming methods of working the alloys ("stirring" them, in effect) followed by prolonged heating is necessary to discover what the trend toward equilibrium really is. When this is done the indications are that at temperatures at or below about 570°F. the equilibrium state shown in Fig. 7 would result. In contrast, Fig. 8 shows the distribution of the alpha iron-chromium and the gamma iron-nickel phases and the mixed phase regions over their respective composition ranges when the alloys are rapidly cooled from the temperature level of Fig. 5.

A wide variety of iron alloys essentially carbon free but carrying either chromium or nickel, or both, to the extent of perhaps 8 or 10%, become martensitic as to structure after even a moderately rapid cooling from the austenitic

temperature. The hardness, although definitely greater in this condition than when composed of polyhedral ferrite grains, is not comparable with the martensite of carbon steel carrying even as little as a quarter of one per cent carbon. These carbonless martensitic structures serve to indicate that the acicular mode of transformation relates to the low transformation temperature rather than to composition.

Apart from the behavior of the brittle compound, the only significant difference between slow and rapid cooling within the ordinary range of rates is observed with low alloy content, when the alpha iron product is "massive" or polyhedral ferrite in the former instance and martensite in the latter; but beyond a few per cent of nickel or of chromium the transformation product is always a "carbonless" martensite.

Furthermore, the alloys which are shown as being wholly or largely ferritic in Fig. 7 (which represents equilibrium conditions at 570°F.), and as being normally austenitic in Fig. 8 (which represents maximum

austenite retained by rapid cooling to room temperature), are subject to inordinate hardening by cold work, that is, in the manner of Hadfield's manganese steel. This extraordinary pick up of strength and hardness is regarded as being due to the formation of ferrite from austenite at a room temperature at which the condition of the ferrite must be that of martensite. This view is strengthened by the observation that higher carbon content enhances this hardening effect of cold work. In any event, this hardening, accompanied by the acquisition of ferromagnetism denotes an allotropic change in an unstable alloy brought about by the stirring action of cold deformation.

Since the compositions carrying about 18% chromium and about 8% nickel are commercially familiar, the sections of the ternary diagram representing each of these two constant concentrations, with the other element variable, are shown in Fig. 9. A somewhat more extended assortment of constant chromium sections is shown in Fig. 10.

The practical usefulness of a discussion of the iron-chromium-nickel system is increased by some consideration of the effects of carbon since it is extremely difficult to produce the alloys free from carbon. The solubility of carbon in the austenite-nickel (gamma iron) solid solutions rapidly decreases as the chromium content increases. Graphite may form in the high nickel alloys with low chromium. The characteristic influence of carbon upon the commercial austenitic iron-chromium-nickel alloys is exemplified in Fig. 11 for the 18 chromium-8 nickel alloy. This shows the state of affairs to be found at equilibrium and is far different from what is ordinarily encountered, as shown in Fig. 12, owing to the extreme sluggishness and negligible reaction rate at the lower temperatures.

Nickel lowers the dissolution rate of its solid solution in iron in essentially all reagents, and hence retards corrosion. When this effect is superimposed upon the passivating effect of chromium when present in excess of some 10%, an unusual resistance to any attack under oxidizing conditions is conferred upon the alloy. When, then, nickel and chromium are so added as to produce an austenitic, work hardening alloy, remarkable properties are realized, as in the "18-8" composition now widely employed.

Under the special case of gaseous corrosion in which atmospheric oxygen attacks metal at elevated temperatures, the iron-nickel-chromium alloys are likewise remarkable. Fortunately, these higher chromium-nickel alloys also possess good strength at elevated temperatures, and this combination of slow oxidation and good high temperature strength makes these materials almost indispensable in the various chemical industries.

In this article little can be included of the industrial significance of the commercial, carbon-bearing, iron-nickel-chromium alloys, and the reader is therefore referred to the chapters on "Stainless Steels" in this handbook.

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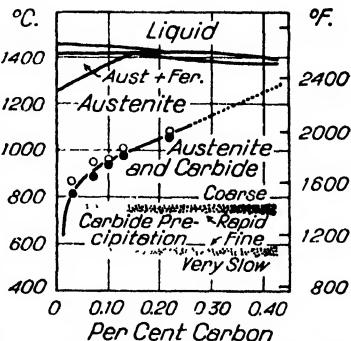


Fig. 12—Schematic chart of carbon solution and precipitation in the 18 chromium-8 nickel alloys.

Properties of Iron and Iron Alloys

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Physical and Mechanical Properties of Iron

By Reid L. Kenyon*

General—The purpose of this article is to give a condensed statement of the physical and mechanical properties of the metal, iron, as reported in scientific literature.

Acknowledgment—The data and information for this article have been selected from a number of sources, but mainly from the book, "The Metal—Iron" by H. E. Cleaves and J. G. Thompson, edited by Frank T. Sisco, and published by the Engineering Foundation, New York. This very complete volume contains an extensive bibliography of over one thousand references. The statements and data from the volume, "The Metal—Iron", have been freely used in the compilation of this article, and the cuts are reproduced by permission of the Engineering Foundation.

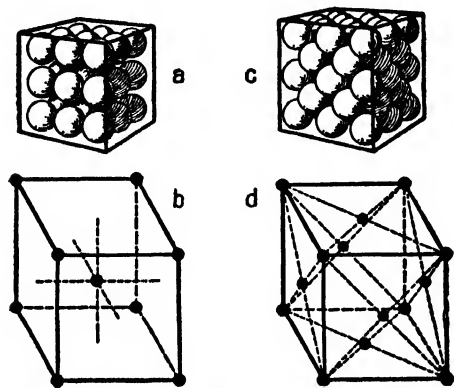


Fig. 1—Crystalline form of iron. (a) Body-centered cubic packing, alpha and delta iron; (b) alpha and delta iron, body-centered cubic; (c) face-centered cubic packing, gamma iron; and (d) gamma iron, face-centered cubic.

Also, data were selected from the U. S. Bureau of Mines Bulletin No. 296, by O. C. Ralston. Data from other sources have been selected and in such cases an endeavor has been made to give credit to the particular author.

The data are usually from tests on material prepared by special methods in the laboratory, so it must be appreciated that considerable variation in the property values must result in many cases. An attempt has been made, as far as the data were available, to include the results of tests on commercially available materials, such as carbonyl iron, electrolytic iron, and ingot iron.†

On account of the variability in composition and treatment of the many different samples of iron used by various investigators, the values given should be considered as the best approximations now available for the different properties and should not be used for specification purposes.

Composition—Table I gives the typical composition of several common forms of iron which are available commercially. The analyses of a number of individual

Table I
Typical Composition of Commercial Irons

C	Mn	P	S	Si	Cu	Ni	O ₂	N ₂	Description
0.012	0.017	0.005	0.025	Trace					Armco ingot iron
0.006	.....	0.005	0.004	0.005					Electrolytic iron
.....	0.001	.....	Trace	0.015	0.004	0.004			Kahlbaum iron
0.005	0.028	0.004	0.003	0.0012			0.003	0.0001†	Hydrogenized iron
0.0007 }	•	•	•	•	•	•	<0.01		Carbonyl iron
0.00016 }									

*Unable to identify, also Cr, Co, Mo, and Zn.

†Total reported impurities 0.024%.

samples used by various investigators in determining various property values are given elsewhere in this article.

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†In this article "Ingot iron" refers to "Armco ingot iron."

Atomic Structure

Isotopes—The Aston mass spectrograph has shown the existence of two isotopes, Fe (54) and Fe (56), which are present in the proportions of 1-20.

Atomic Number—The atomic number is 26.

Atomic Weight—The atomic weight is 55.84.

Nuclear Structure—The nucleus of the iron atom consists of 14 alpha particles and two negative charges. The nucleus therefore carries a 26-fold positive charge

which is compensated by the 26 electrons in the outer shells. The ratio of the number of outer electrons to the total positive charges is 0.536. This quantity is a measure of the nuclear stability which is quite large for iron.

Arrangement of Electrons—The 26 outer electrons are believed to be distributed on four shells as follows: The inner K-shell 2, L-shell 8, M-shell 14, and the outer N-shell 2.

Atomic Radius—As reported by Morse, the atomic radius for alpha iron is 1.236×10^{-8} cm. and for gamma iron is 1.284×10^{-8} cm.

Atomic Volume—By this term is usually meant the volume of a gram-molecular weight, and for iron at room temperature this is 7.1 cm.³ The volume of an individual atom can be derived from this by dividing by Avagadro's number which gives 11.7×10^{-24} cm.³ for alpha iron at 16°C.

Crystallographic Properties—Iron is found to have two crystallographic forms: Body-centered cubic for alpha, beta, and delta iron, and face-centered cubic for gamma iron (Fig. 1). The dimensions of the unit cube (lattice parameter) vary with temperature as shown in Fig. 2. The body-centered cubic lattice can be considered as two interpenetrating simple cubic lattices whose coordinates are (0 0 0)

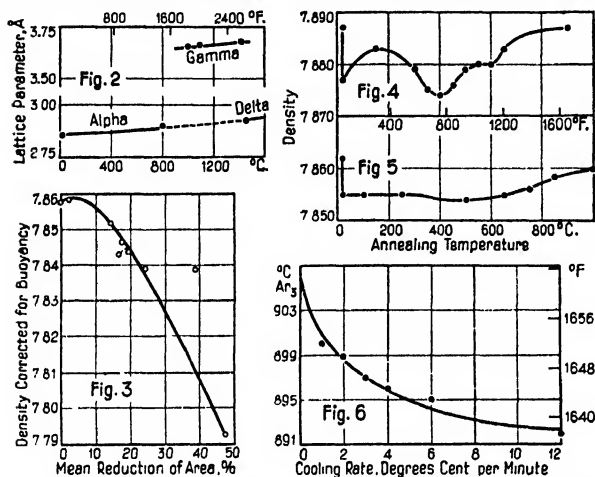


Fig. 2—Effect of temperature on lattice parameter of iron. (Sato.) Fig. 3—Effect of cold work on the density of ingot iron. (O'Neil.) Fig. 4—Effect of annealing on the density of cold drawn ingot iron (Tamaru) Fig. 5—Effect of annealing on the density of cold hammered ingot iron. (Ishigaki.) Fig. 6—Effect of cooling rate on Ar₃ point of iron. (Goertens.)

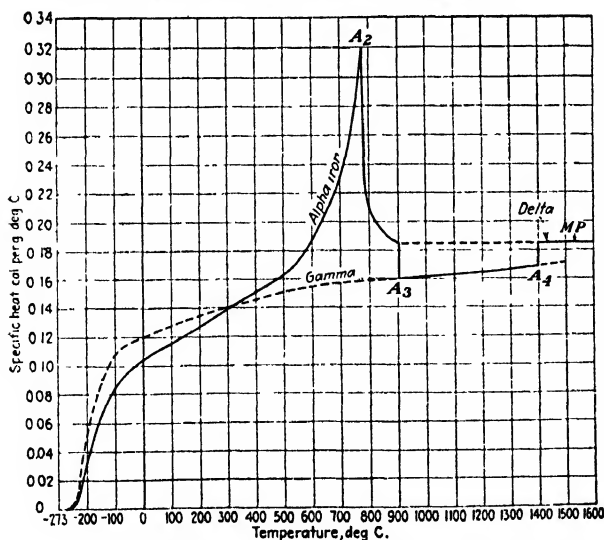


Fig. 7—Specific heat of iron. (Austin.)

and $(\frac{1}{2} \frac{1}{2} \frac{1}{2})$. The face-centered lattice is really made up of four interpenetrating simple cubic lattices and there are, therefore, four atoms in the elementary cell whose coordinates are (0 0 0) $(\frac{1}{2} 0 \frac{1}{2})$ $(\frac{1}{2} \frac{1}{2} 0)$ and $(0 \frac{1}{2} \frac{1}{2})$.

Density—The density determinations on individual specimens may be conducted with great precision but the results apply only to the small pieces used in the test and results carried out to several significant figures are therefore of questionable value, at least as a measure of the density of the material as a whole. Three common methods for determining density of iron are: Direct measurement, calculation from the lattice constant as determined by X-ray examination, and extrapolation to zero content of alloying element of a series of iron alloys. Table II gives average values computed by Cleaves and Thompson from the work of a number of investigators.

Variation of Density with Temperature—The density at temperatures above room temperature are generally determined by calculation from either the coefficient of thermal expansion or the lattice constants. Lack of accurate data on

Table II
Density of Iron at Room Temperature

Average Values by Direct Measurement, Calculation from Lattice Constant and Extrapolation

Type of Iron	Direct Measurement	Calculated from Lattice Constant	Extrapolation
Ingot	7.866		
Carbonyl	7.860		
Electrolytic	7.874		
Variety of 50 samples		7.865	
			7.868

Table III
Density of Iron at Elevated Temperature*

Temp.		Density (g. per cc.)			Molten Iron
°C.	°F.	(1)	(2)	(3)	
100	212	7.85			
200	390	7.82			
300	570	7.78			
400	750	7.74			
500	930	7.71			
600	1110	7.67			
700	1290	7.63			
800	1470	7.59			
{800—	{1472—				
{825	{1517		7.55		
906	1663			7.571 (alpha)	
906	1663			7.663 (gamma)	
1400	2552			7.408 (gamma)	
1400	2552			7.390 (delta)	
1425	2597		7.32		
Melting Point					6.92 ± 0.07
1530	2785				7.45
1530	2785				7.38
1533	2790				7.23
1535	2795			7.355 (delta)	
1535	2795				7.10
1600	2910				7.16
1670	3040				6.94

*Data in column (1) calculated by Cleaves and Thompson from thermal expansion data of Souder and Hidnert and of Austin and Pierce with 7.87 g. per cc. as the density of iron at 25°C. Column (2) calculated from lattice constants determined by Westgren and Phragmen. Column (3) calculated by Ralston from thermal expansion data of Honda and Sato.

volume changes at the transformation points results in the values for density above the A₂ point being unsatisfactory. Table III combines data from several sources on the density of iron at elevated temperature.

Variation of Density with Cold Working—Cold working lowers the density of iron as shown by the data obtained by O'Neill on ingot iron, Fig. 3. Tamaru and Ishigaki studied the effect of annealing at various temperatures on the density of cold worked ingot iron and their results are shown in Fig. 4 and 5. When heated above the A₂ point, the density is restored to the value it had before cold working.

Transformation Points—The transformation points are the temperatures at which the various polymorphic changes occur. Some of these points are well accepted, while others are in much question, being merely discontinuities in some physical property curve.

Owing to the wide variation in the methods used for determining these transformation points, considerable difference in the results is to be expected. Some of the methods that have been used are: Heating and cooling curves and variations of this method, including differential curves; calorimetric measurements; magnetic tests; thermoelectric phenomena; electrical resistance measurements, and dilatation.

A₁ Transformation Range—This is the Curie point of pure iron below which iron is magnetic and above which it is not. X-ray methods have shown paramagnetic α iron (formerly called β) to be of the same crystal structure as magnetic α iron. The magnetization is not all lost at one point, most of it being gone on heating up to 768°C., but remaining traces being detectable up to 791°C. This upper temperature depends on the sensitiveness of the instruments used.

Heating and cooling curve methods have yielded quite consistent results and for several investigators show that the greatest thermal effect of the A₁ transition

occurs at 768°C. Sauveur has found that previous heat treatment has some effect on the determination, successive heatings tending to gradually raise the value to a constant temperature.

Calorimetric methods have been used by many investigators, and Ralston has studied and interpreted their data and gives an average value of 781°C. corresponding to the discontinuity in heat content.

Values obtained by means of magnetic tests are influenced by strength of field and sensitiveness of instruments. As already stated, the magnetic effect falls off rapidly at about 768°C., but Honda claims it does not reach a constant value until about 790°C.

Thermocouples made of iron and platinum or iron and copper have been used for determination of the transformation points, but contamination of the couples has been one frequent source of error in these measurements.

Broniewski and Belloc found a discontinuity in the emf.-temperature curve at about 795°C. The work of Burgess and Scott showed a definite change in direction of the curve at 768°C. This was an electrolytic iron sample against platinum. All of their curves (for heating) had maxima at about 780°C. It has been suggested by Ralston that the latter is the real A₁ point as revealed by thermoelectric means, the 768°C. point being due to heat absorption known to reach a maximum at that temperature.

Some experimenters have reported discontinuities in the electrical resistance curve at a temperature corresponding to the A₁ point. For example, Honda and Ogura report such a point at 798°C. Burgess and Kellberg used a method estimated to give a precision 1,000 times greater than that of Honda and Ogura and found a perfectly smooth curve. This would indicate that electrical resistance data fail to show the existence of the A₁ point.

The only evidence available on the dilatometric changes corresponding to the A₁ point are those contributed by Benedicks whose dilatometric measurements have been accepted as precise, but whose temperature measurements and control have been criticized. His data show a slight indication at 760-775°C., but this is subject to interpretation.

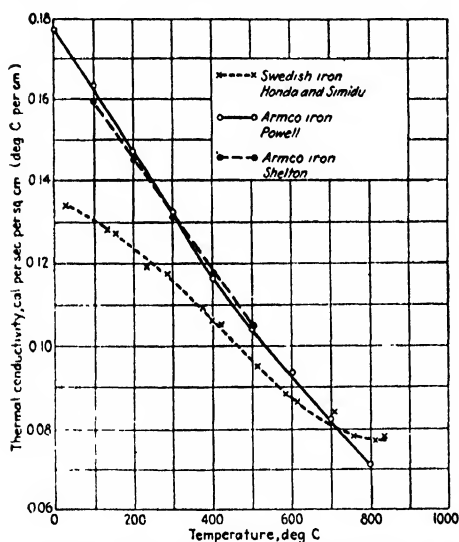


Fig. 8—Effect of temperature on the thermal conductivity of iron.

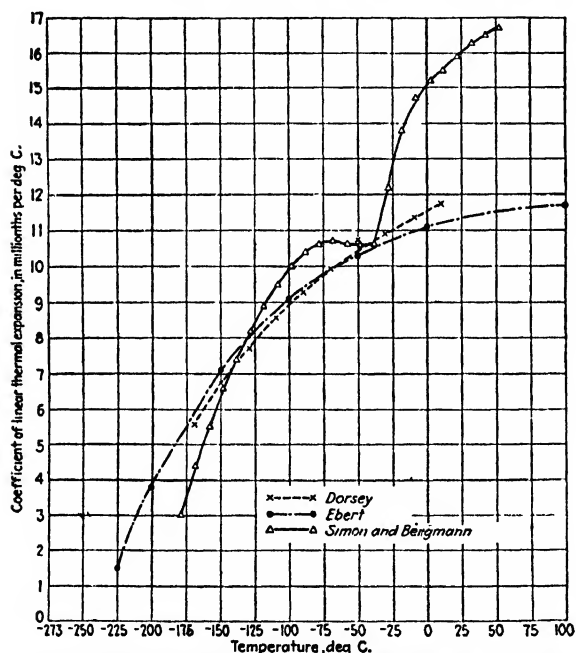
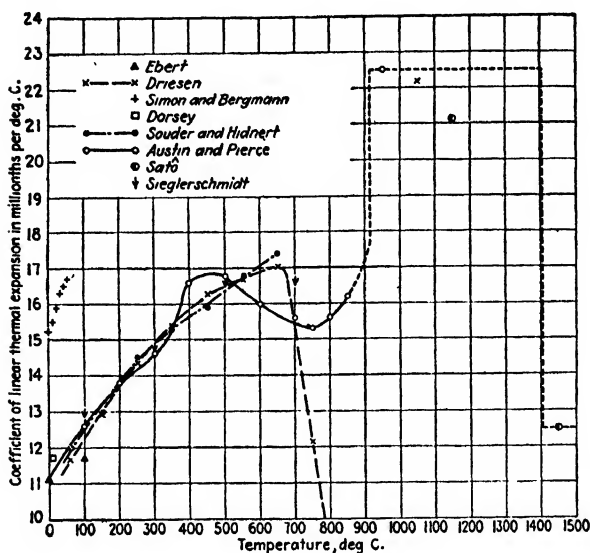


Fig. 9.—Coefficient of linear thermal expansion of iron at low and high temperatures.

A₂ Transformation Range—This is the temperature at which pure iron undergoes a crystallographic change from a body-centered to a face-centered cubic lattice. The change is not instantaneous and consequently there is some difference between the transition temperature on heating and cooling and also with variation in heating and cooling rate. Values are given for A_c (heating) and A_r (cooling). Ralston believes the best values to be those of Burgess and Crowe, who tried several cooling and heating rates and extrapolated to zero rate. Their corrected figures for zero rate are A_c, 909 ± 1°C., and A_r, 898 ± 2°C. These values are determined from the heating and cooling curves. Oberhoffer quotes the later work of Ruer and F. Goerens, which established the $\gamma \rightleftharpoons \beta$ transformation at 906°C. ± 1° (Fig. 6).

The specific heat method is regarded as giving the value for A_c and the method of carrying out such tests gives results corresponding to zero heating rate. Oberhoffer and Grosse, and Umino both report 906°C., but the values are not considered precise.

Magnetic methods give the values in Table IV.

Table IV
Experimental Values for A₂ Transformation Points Determined by Magnetic Methods

Observer	Date	A _c , °C.	A _r , °C.
Honda and Takagi.....	1915	911	898
Honda and Takagi.....	1915	908	889
Ishiwara	1917-18	898	890
Terry	1917	918	903

Thermoelectric methods using platinum for reference have been used by Burgess and Scott. They found that the A_c transition begins at 906°C. on heating and continues to 912°, while the A_r transition begins at 900°C. on cooling and is complete at 896°C. Later work by Berliner confirmed these temperatures.

Electrical resistance methods are not so sensitive as some of the others, but Burgess and Kellberg, by using high precision methods, showed A_c beginning at about 900°C. and continuing to 911°C., while A_r began at about 887°C. and finished at 872°C.

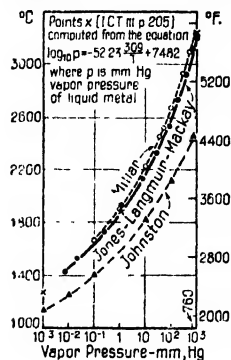


Fig. 10—Effect of temperature on the vapor pressure of iron.

Honda and Miura working with ingot iron at heating or cooling rates of 2°C. per min. found A_c begins at 860°C. and ends at 905°C., while A_r begins at 889°C. and ends at 850°C. Recent work on hydrogen annealed carbonyl iron showed a spread of only 2 or 3°C. and even of only 1°C. between A_c and A_r temperatures. An A_c value of $907 \pm 2^\circ\text{C.}$ was obtained using a heating rate of 0.125°C. per min., while the A_r point for the same cooling rate was 907°C. Cleaves and Thompson observe that "the spread between A_c and A_r points can be practically eliminated by technique and methods which are now available, but further work is necessary to decide whether or not the temperature of the A_c transformation is appreciably higher for extremely pure iron than for somewhat less pure material."

A_c Transformation Range—Magnetic and thermal tests are the principal ones that have been used to determine this point. It was first discovered by Ball and later by Osmond and Curie. The samples of these investigators were impure, which is no doubt the reason for their low results (1300°C.). More recent determinations are given in Table V.

Table V
Experimental Values for A_c Transformation Point

Observers	Date	A_c , °C.
Thermal Methods:		
Gontermann	1908	1411
Ruer and Kaneke.....	1914	1420
Ruer and Klesper.....	1914	1401
Hanson and Freeman.....	1923	1400
Wever	1927	1401
Magnetic Method:		
Weiss and Foex.....	1911	1395
Ishiwara	1917	1390
Terry	1917	1406

Ralston gives the above values (except Wever) and concludes that the work of Ruer and Klesper and of Terry seems to be the most consistent and best described, and averages their data to get A_c at 1403.5°C.

Specific heat determinations of Wüst, Meuthen, and Dürrer showed A_c to be at 1404.5°C., while Oberhoffer and Grosse found it to be at 1401°C. As Ralston points out, these methods are not as precise as magnetic or thermal tests but give good confirmation of the above values determined by those methods.

Heat Capacity, Specific Heat, Entropy—Although considerable data have been published on these properties, there are numerous discrepancies between them which makes a concise presentation difficult. Both Ralston and Austin have made critical surveys of the results available. Cleaves and Thompson prefer Austin's review because it is more recent than Ralston's and includes data obtained by improved methods.

The variation in specific heat with temperature is shown in Fig. 7. In this discussion "specific heat" refers to the rate of change of heat content at a given temperature (sometimes called "true specific heat" in the literature), and "mean specific heat" refers to the average rate of change over a given temperature range.

Table VI, adapted from Cleaves and Thompson, gives values selected by Austin for entropy, heat content, free energy, and specific heat of both alpha and gamma iron over the entire range from absolute zero to the melting point. The specific heat of liquid iron has been reported by various investigators (Wüst, Meuthen, and Dürer; Umino; Oberhoffer and Grosse), at values varying from 0.142-0.222 cal. per g. The average of four reported data is 0.177 cal. per g.

Table VI
Specific Heat, Heat Content, Free Energy, and Entropy

°K.	Temp °C.	°F.	Alpha Iron					
			Specific Heat cal./g.°C. atom °C.		Heat Content (H) Referred to H = O at 0°K. cal./g. atom		Free Energy (F) cal./g. atom	Entropy (S) cal./g. atom °C.
0	-273.1	-459.6	0	0	0	0	0	0
20	-253.1	-423.6	-	0.005	-	-	-	-
23	-250.1	-418.2	-	-	-	-	-	-
30	-243.1	-405.6	0.003	0.105	-	-	-	-
40	-233.1	-387.6	0.007	0.367	-	-	-	-
50	-223.1	-369.6	0.013	0.710	0.09	5	-8	0.248
73	-200.1	-328.2	-	-	-	-	-	-
75	-198.1	-324.6	0.032	1.80	-	-	-	-
100	-173.1	-279.6	0.051	2.85	1.88	105	-45	1.40
123	-150.1	-238.2	-	-	-	-	-	-
125	-148.1	-234.6	0.065	3.65	-	-	-	-
150	-123.1	-189.6	0.077	4.33	5.20	290	-134	2.83
173	-100.1	-148.2	-	-	-	-	-	-
175	-98.1	-144.6	0.088	4.80	-	-	-	-
200	-73.1	-99.6	0.092	5.15	9.4	525	-303	4.24
223	-50.1	-58.2	-	-	-	-	-	-
225	-48.1	-54.6	0.097	5.40	-	-	-	-
250	-23.1	-8.6	0.101	5.66	14.5	810	-572	5.53
273.1	0	32.0	0.104	5.84	17.0	950	-715	6.10
283	10	50.0	0.1060	5.919	-	-	-	-
293	20	68.0	0.1075	6.002	-	-	-	-
298	25	77.0	0.108	6.061	19.6	1096	-871	6.60
303	30	86.0	0.1087	6.070	-	-	-	-
313	40	104.0	0.1097	6.126	-	-	-	-
323	50	122.0	0.1105	6.170	22.4	1250	-1014	7.01
333	60	140.0	0.1112	6.209	-	-	-	-
343	70	158.0	0.1119	6.248	-	-	-	-
353	80	176.0	0.1126	6.288	-	-	-	-
363	90	194.0	0.1133	6.322	-	-	-	-
373	100	212.0	0.1141	6.395	28.0	1566	-1455	8.10
423	150	302.0	0.121	6.78	33.9	1894	-1887	8.94
473	200	392.0	0.128	7.13	40.2	2246	-2389	9.80
523	250	482.0	0.134	7.48	46.7	2610	-2850	10.44
573	300	572.0	0.140	7.82	53.7	2998	-3368	11.11
623	350	662.0	0.146	8.14	60.8	3394	-3970	11.82
673	400	752.0	0.151	8.43	68.2	3814	-4685	12.48
723	450	842.0	0.157	8.74	76.0	4244	-5206	13.07
773	500	932.0	0.163	9.10	84.0	4689	-5911	13.72
823	550	1022.0	0.172	9.58	92.4	5159	-6581	14.26
873	600	1112.0	0.188	10.54	101.2	5653	-7293	14.83
923	650	1202.0	0.208	11.62	111.1	6204	-8028	15.42
973	700	1292.0	0.230	12.84	122.0	6810	-8894	16.14
1023	750	1382.0	0.276	15.40	133.4	7451	-9460	16.53
1033	760	1400.0	0.320	17.89	-	-	-	-
1073	800	1472.0	0.210	11.70	146.0	8151	-10573	17.45
1123	850	1562.0	0.194	10.84	156.5	8737	-11566	18.08
1173	900	1652.0	0.186	10.39	165.6	9250	-12427	18.48
1179	906	1662.0	0.160	9.94	166.4	9294	-12500	18.51
1223	950	1742.0	-	-	174.9	9765	-13300	18.86
1273	1000	1832.0	-	-	184.1	10280	-14251	19.27
1323	1050	1922.0	-	-	193.5	10795	-15215	19.66
1373	1100	2012.0	-	-	202.5	11310	-16219	20.05
1423	1150	2102.0	-	-	211.8	11825	-17233	20.42
1473	1200	2192.0	-	-	221.0	12340	-18239	20.76
1523	1250	2282.0	-	-	230.3	12855	-19325	21.13
1573	1300	2372.0	-	-	239.4	13370	-20339	21.43
1623	1350	2462.0	-	-	248.6	13885	-21448	21.77
1673	1400	2552.0	-	-	257.9	14400	-22540	22.08
1723	1450	2642.0	-	-	267.1	14915	-23645	22.38
1773	1500	2732.0	-	-	276.3	15430	-24782	22.68
1808	1535	2795.0	-	-	282.8	15791	-25400	22.88

(Continued)

Table VI—Continued
Specific Heat, Heat Content, Free Energy, and Entropy

Gamma Iron										
°K.	Temp. °C.	°F.	Specific Heat		-Heat Content (H ₁)- Based on H ₁ = 0 at 0°K.		-Heat Content (H ₂)- H ₂ = 960 at 0°K.		Free Energy (F) cal./g.- atom	Entropy (S) cal./g.- atom °C.
			cal./g.°C.	atom °C	cal./g.	atom	cal./g.	atom		
0	-273.1	-459.6...	0	0	0	0	17.19	960	960	0
20	-253.1	-423.6...	-	0.10						
23	-250.1	-418.2...			0.018	1 0	17.21	961	957	0.06
30	-243.1	-405.6...	0.004	0 25						
40	-233.1	-387.6...	0.010	0.53						
50	-223.1	-369.6...	0.024	1.36						
73	-200.1	-328.2...			1.196	66.8	18.37	1026	939	1.20
75	-198.1	-324.6...	0.052	2 90						
100	-173.1	-279.6...	0.071	3.95						
123	-150.1	-238.2...			4.67	261	21.9	1221	842	3.08
125	-148.1	-234.6...	0.089	5.00						
150	-123.1	-189.6...	0.100	5.60						
173	-100.1	-148.2...			9 63	538	26 8	1498	636	4 98
175	-98.1	-144.6...	0 109	6.10						
200	-73.1	-99.6...	0.114	6.35						
223	-50.1	-58.2...			15.4	862	32 6	1822	336	6.66
225	-48.1	-54.6...	0 116	6.50						
250	-23.1	-9.6...	0 118	6.60						
273.1	0	32.0...	0 120	6.70	21.2	1185	38 4	2145	-12	7.90
283	10	50.0...								
293	20	68.0...								
298	25	77.0...	0.122	6 80	24 3	1357	41 5	2317	-228	8.54
303	30	86.0...								
313	40	104.0...								
323	50	122.0...	0 124	6 90	27 5	1529	44.6	2489	-420	9.00
333	60	140.0...								
343	70	158.0...								
353	80	176.0...								
363	90	194.0...								
373	100	212.0...	0 127	7.11	33.7	1880	50.5	2840	-967	9 94
423	150	302.0...	0 131	7 30	40.2	2244	57.6	3214	-1377	10.83
473	200	392.0...	0.134	7.49	46.9	2617	64.1	3577	-1933	11.65
523	250	482.0...	0.137	7 67	53 65	2996	70.8	3956	-2550	12.44
573	300	572.0...	0.141	7 86	60.6	3384	77 8	4344	-3185	13.14
623	350	662.0...	0 143	8 01	67.7	3781	84 9	4741	-3856	13.80
673	400	752.0...	0.146	8 18	75.0	4186	92 2	5146	-4545	14.40
723	450	842.0...	0 148	8 30	82.4	4601	99.6	5561	-5284	15.00
773	500	932.0...	0 151	8 43	89 8	5016	107.0	5976	-6083	15.60
823	550	1022.0...	0 153	8 54	97 5	5442	114.6	6402	-6807	16.06
873	600	1112.0...	0 155	8 66	105.1	5872	122.4	6832	-7607	16.54
923	650	1202.0...	0 156	8.71	112.9	6307	130.1	7267	-8452	17.03
973	700	1292.0...	0 157	8 77	120.8	6744	136.2	7604	-9314	17.49
1023	750	1382.0...	0 158	8.81	128.7	7184	145.8	8144	-10116	17.85
1033	760	1400.0...								
1073	800	1472.0...	0.158	8 88	136.5	7625	153.7	8585	-11083	18.33
1123	850	1562.0...	0.159	8 91	144.5	8069	161.7	9029	-11971	18.70
1173	900	1652.0...	0.160	8 98	152.5	8515	169.7	9475	-12954	19.13
1179	906	1662.0...	-	-	153.3	8552	170.3	9512	-13004	19.17
1223	950	1742.0...	0 161	8.99	160.5	8961	177.7	9921	-13524	19.50
1273	1000	1832.0...	0.162	9.02	168.5	9411	185 7	10371	-14911	19.86
1323	1050	1922.0...	0 162	9.05	176.6	9862	193 8	10822	-15916	20.21
1373	1100	2012.0...	0.163	9.10	184.8	10319	202 0	11279	-16940	20 55
1423	1150	2102.0...	0 164	9 16	192 9	10774	210.1	11734	-17964	20 87
1473	1200	2192.0...	0.165	9 21	201 2	11234	218.1	12194	-19020	21.19
1523	1250	2282.0...	0 166	9 27	209.4	11695	226 6	12655	-20120	21.52
1573	1300	2372.0...	0 167	9 32	217.8	12160	236.6	13120	-21171	21.80
1623	1350	2462.0...	0.168	9 38	226.1	12627	242.8	13587	-22265	22.09
1673	1400	2552.0...	0.169	9 44	234.6	13098	251.8	14058	-23367	22.37
1723	1450	2642.0...	0 170	9.50	243.0	13571	260.2	14531	-24495	22.65
1773	1500	2732.0...	0.171	9 56	251.6	14048	268.8	15008	-25630	22.92
1808	1535	2795.0...								

Heats of Transition—There is no discontinuity in the total heat curve at the A₂ point and Ralston interprets this as indicating only a change in specific heat and not a real heat of transition. Numerous values of heat of transformation are given in the literature for the A₂ point, but these may be the magnetic component of the specific heat integrated over a more or less wide range of temperature. Ralston states: "The true heat of transition of A₂ is therefore zero, unless we look on the heat accompanying the magnetic changes as a distributed (over a tempera-

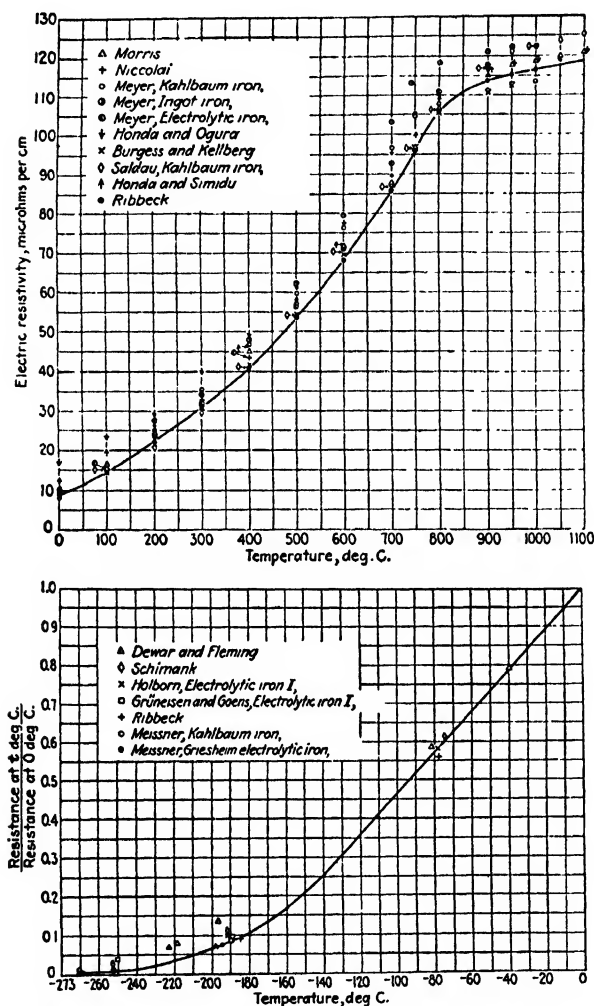


Fig. 11—Electric resistance of iron at low and elevated temperatures.

Austin considered Ralston's value as the most probable one for the heat effect at the A point.

ture range) latent heat. This latter idea is quite permissible, although not in common acceptance."

The values for heat of transition at the A point have for the most part been determined by measuring the heat content above and below the transition temperature; and since the results are small differences between large numbers, the variations recorded in the literature are not surprising. Since Ralston calculated his value of 4.9 cal. per g. from an average heat content curve, Klinkhardt and Esser and Bunghardt have made direct determinations of the heat absorbed during the transformation. The average of their results gives 3.63 cal. per g. or 203 cal. per g.-atom.

Yap computed, from Umino's heat content data, the heat effect during the alpha-gamma change when this occurred at various temperatures.

Although Ralston's value of 1.7 cal. per g. or 94.9 cal. per g.-atom for the heat effect at the A point is somewhat lower than Umino's subsequently reported determination of 1.86 cal. per g., Cleaves and Thompson state that

Table VII
Variation of Heat Effect at A₂ Point with Temperature

Temp. of Transformation, °C.	Heat Effect cal. per g.	Temp. of Transformation, °C.	Heat Effect cal. per g.
200	22.4	1000	3.2
400	22.6	1100	1.2
600	18.4	1200	-0.3
800	8.5	1300	-1.5
900	5.6	1400	-1.9

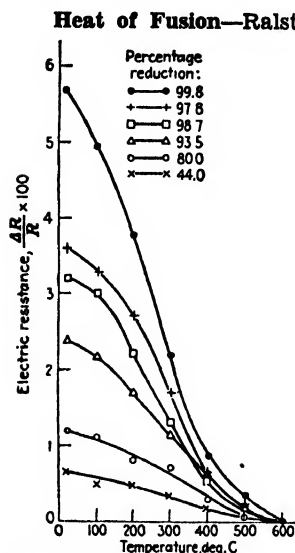


Fig. 12—Effect of annealing on the electric resistance of cold worked iron.

Thermal Conductivity—Most of the published determinations of this property are for impure specimens. This no doubt accounts for much of the disagreement between the results of different workers, although Grüneisen and Goens found that impurities had a much greater effect at low temperatures than at room temperature. The data from several sources are shown in Fig. 8.

Thermal Coefficient of Expansion—The coefficient linear thermal expansion is the increase in length per unit length for 1° rise in temperature, and is sometimes referred to as the "true coefficient of expansion." The average expansion over a range of temperature is the mean coefficient of expansion over that range.

Fig. 9 shows the results reported by various investigators, while Table VIII gives values selected by Cleaves and Thompson. Mean coefficients for various temperature ranges are given in Table IX.

Table VIII
Coefficient of Linear Expansion of Alpha Iron

Temp., °C.	Coefficient of linear expansion, millionths per °C.	
	By Austin and Pierce	By Sieglerschmidt
100.....	12.6	12.9
200.....	13.8	
300.....	14.6	14.7
400.....	16.6	
500.....	16.8	16.5
600.....	16.0	
700.....	15.6*	16.5
750.....	15.3*	
800.....	15.6*	
850.....	16.2*	

Austin and Pierce found that the expansion above 600°C. was sensitive to small changes in composition and treatment, and they did not give selected values above that temperature. The ones marked () were averages by Cleaves and Thompson, not for precise values but to indicate the trend of the relation for higher temperatures.

The thermal coefficient of expansion for gamma iron is given in Table IX; that for delta iron has been reported by Sato to be 16 millionths per °C. Ralston recalculated Sato's data and got 12.5 millionths per °C., while calculations based on Schmidt's X-ray data gave 19.5 millionths per °C.

The expansivity of molten iron has been calculated from density determinations but shows wide variations according to the data used. Berlin's data yield 0.00043 as the coefficient of cubical expansion per °C. between the melting point and 1700°C., while the results of C. Benedicks, N. Ericsson, and G. Ericson give 0.00014 per °C. between the melting point and 1600°C.

The thermal expansion at the transformation points has been investigated in the course of determinations of these points but may be summarized here. There is no agreement regarding the occurrence of a definite amount of expansion at the A_s point; certain maxima and minima have been reported at various temperatures, but even these are not consistent. There is a sudden contraction as iron is heated through the A_s range. Although this change is generally considered to be reversed

Table IX
Mean Coefficient of Thermal Expansion of Alpha and Gamma Iron

Driesen		Maurer and Schmidt		Souder and Hidnert		Esler and Müller		Schmidt		Austin and Pierce	
Temp. Interval, °C.	Mean Coefficient, Millionths per °C.	Temp. Interval, °C.	Mean Coefficient, Millionths per °C.	Temp. Interval, °C.	Mean Coefficient, Millionths per °C.	Temp. Interval, °C.	Mean Coefficient, Millionths per °C.	Temp. Interval, °C.	Mean Coefficient, Millionths per °C.	Temp. Interval, °C.	Mean Coefficient, Millionths per °C.
Alpha Iron											
20-100	11.66	20-50	11.30	25-100	12.0	.....	13.98	20-100	11.6	0-100	11.9
100-200	12.93	20-100	11.70	100-200	13.0	13.11	13.54	20-400	12.0	0-200	12.3
200-300	14.23	20-150	12.25	200-300	14.5	13.44	13.71	20-740	12.7	0-300	13.1
300-400	15.34	20-200	12.94	300-400	15.3	13.79	13.98	20-900	13.6	0-400	13.7
400-500	16.27	20-250	13.40	400-500	15.9	14.29	14.28	20-1400	16.2	0-500	14.4
500-600	16.64	20-300	13.71	500-600	16.8	15.04	14.48			0-600	14.7
600-700	17.03	20-350	13.94	600-700	17.4	15.36	14.81			0-700	14.9
700-800	12.12	20-400	14.15	25-300	13.3	15.61	15.03			0-800	14.9
800-900	-5.89	20-450	14.31	300-600	15.9	15.80	15.22				
				25-600	14.7	15.96	15.49				
						16.09	15.72				
						16.20	15.98				
						16.35	16.29				
						16.09	16.23				
						16.13	15.82				
						16.21	15.86				
						16.25	15.73				
Gamma Iron											
900-1000	22.18			906-945	23.4	25.81	24.14	920-1400	24.1		22.5
						25.53	23.87				
						25.44	23.96				
						25.53	24.01				

on cooling, Austin and Pierce and others have found that the expansion on cooling was less than the contraction on heating in the case of the purest specimens tested. Cleaves and Thompson give the results of several investigators and the values vary from 0.82-3.8 thousandths (linear change at the A_1 point, $\Delta L/L$). The metal expands suddenly at the A_1 point, the only direct determination being by Sato as 0.851 thousandths $\Delta L/L$. Calculations based on X-ray data give from 1.4-3.2 thousandths $\Delta L/L$.

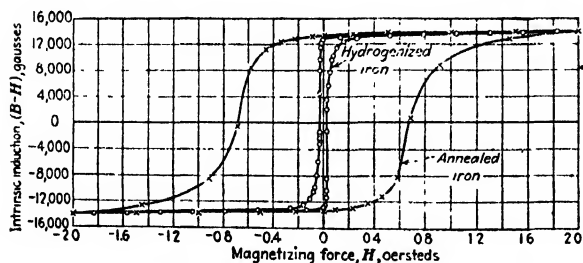


Fig. 13—Hysteresis loop for ingot iron and hydrogenized iron.

facing the difficulty of reconciling this with the later determination† of Jenkins and Gaylor (1527 \pm 3°C.), suggested that the value of 1535°C. (2795°F.) be accepted as a rounded value for the best present approximation of the melting point of iron.

Table X
Vapor Pressure of Iron
Temperatures, °C., as Given by Different Observers

Vapor Pressure mm. Hg.	Johnston	Millar	Jones, et al	International Critical Tables
1.86×10^{-28}			327	
7.58×10^{-10}			427	
2.06×10^{-10}			527	
9.52×10^{-12}			627	
1.32×10^{-10}			727	
7.11×10^{-9}			827	
1.84×10^{-7}			927	
3.22×10^{-6}			1027	
3.47×10^{-5}			1127	
2.70×10^{-4}			1227	
1.00×10^{-3}	1130			1267‡
1.60×10^{-3}			1327	
0.0076			1427	
0.010	1250			
0.023			1527	
0.100	1400	1655		
0.220			1727	
1.000	1590	1900		1884
1.2			1927	
7.5			2127	
10	1820	2225		
26.2			2327	
36		2450		
50	2010	2520		
82.5			2527	
100	2110	2670		
165			2727	
300		2930		
345			2927	
500		3097		
631			3127	
760**	2450	3235	3202	3235

‡Extrapolated below the melting point. All values in this column are extrapolated beyond the experimental range.

**This vapor pressure corresponds to the boiling point under "standard conditions."

*They report the following analyses of three electrolytic irons used in their tests: Langbein-Pfianhauser electrolytic iron, 0.012 C, 0.00 Mn, 0.007 P, 0.00 S, 0.00 Si, 0.008 Cu; C. F. Burgess electrolytic iron, 0.012 C, 0.00 Mn, 0.004 P, 0.00 S, 0.013 Si; J. R. Cain electrolytic iron, 0.004 C, 0.00 Mn, 0.0006 P, 0.004 S, 0.001 Si, 0.008 Cu.

†Jenkins and Gaylor used an electrolytic iron whose composition before melting was 0.005-0.007 C, trace Mn, 0.002 P, 0.0-0.001 S, trace to 0.009 Si, trace to 0.006 Cu, and after melting was 0.01 C, trace Mn, 0.014 P, trace S, 0.03 Si.

Boiling Point and Vapor Pressure—Table X gives the results of several investigators and these are plotted in Fig. 10. The boiling point is the temperature at which the vapor pressure equals 760 mm. of mercury. Cleaves and Thompson suggest that a rounded value of 3000°C. should be used for the boiling point because

the most reliable values available were determined indirectly and under experimental conditions likely to lead to inaccuracies.

Electrical Properties—The electrical resistance of iron is greatly influenced by impurities and by the previous thermal and mechanical treatment so that reported values are often discordant. Cleaves and Thompson give a complete discussion of this subject and the following data are largely abstracted from their presentation.

The average of nine different workers' results for the resistance at 0°C. gave 9.43 microhm-cm. for electrolytic iron, of seven results for reduced iron, 9.29 microhm-cm., and of three for commercially pure open hearth iron, 9.50 microhm-cm., while a single value given for Swedish iron was 13.2 microhm-cm., all at 0°C. Cleaves and Thompson consider a rounded value of 9.8 microhm-cm.

at 20°C. to be the best present approximation for the resistivity of iron. This would be equivalent to 9.67 microhm-cm. at 0°C. using 0.0065 per °C. as the fundamental coefficient.

Fig. 11 gives the electrical resistance of iron from the lowest to the highest temperatures that have been investigated. There are no data available for high purity iron between 1100°C. and the melting point. The values shown for molten iron were obtained by Boremann and Wagenmann by extrapolation to zero carbon content for a series of carbon steels. Table XI combines data from several sources as reported by Cleaves and Thompson. They state that Meissner's values of resistivity are probably the best for sub-zero temperatures, while those of Burgess and Kellberg are considered most probable above zero.

Temperature Coefficient of Electrical Resistance—(Effect of

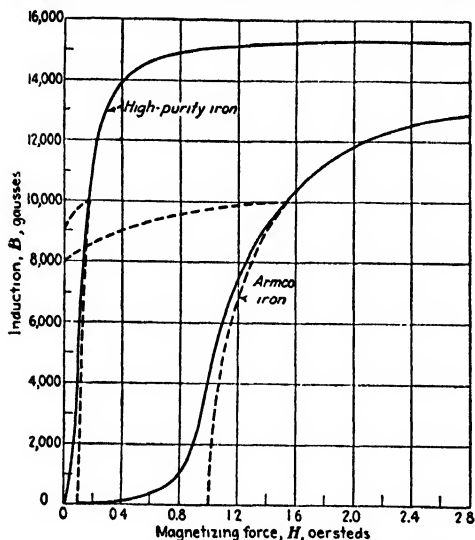


Fig. 14—Magnetization curves for ingot iron and high purity iron. (Yensen.)

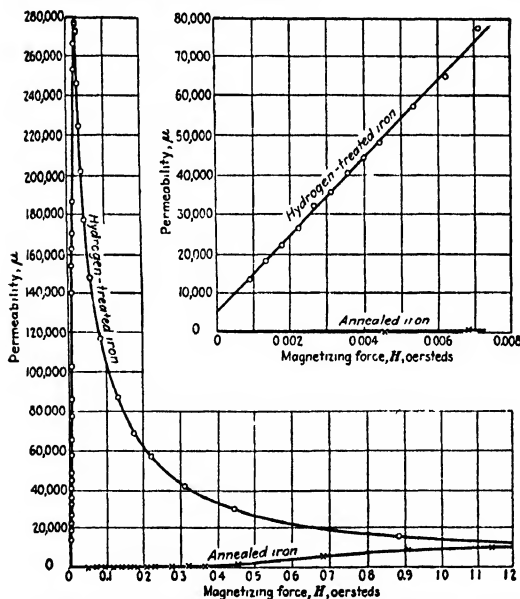


Fig. 15—The effect of hydrogen treatment on the permeability of annealed iron. (Cloff, according to Ellis and Schumacher.)

Temperature on Electrical Resistance). The resistance of iron, like other metals, changes with temperature and the coefficient expressing this relationship, as defined by the following equation, is tabulated for several irons in Table XII.

$$R_t - R_{t'}$$

$$\alpha = \frac{R_t - R_{t'}}{R_{t'}(t - t')}$$

Table XI
Effect of Temperature on Resistivity of Iron

°K.	Temp. °C.	°F.	Electrolytic Iron, Grünelsen and Goens—			
			"H. W." Iron, Fleming	Electrolytic Iron, Meissner	I—Double- Deposited, Worked and Annealed	II—Polycrystal- line, Not Annealed at 500°C.
1.98	-271.22	-456.20	.....	0.0583	.....	.....
4.22	-268.98	-452.16	.....	0.0585	.....	.....
20.2	-253	-423.4	.....	.....	.....	0.1065
20.39	-252.81	-423.06	.....	0.0718	.....	.....
21.2	-252	-421.6	.....	.....	0.068	1.060
50.5	-222.7	-368.9	0.644	.....	.....	.....
50.8	-222.4	-368.32	0.649	.....	.....	.....
51.0	-222.2	-368	0.660	.....	.....	.....
54.2	-219	-362.2	0.725	.....	.....	.....
76.1	-197.1	-322.8	1.220	.....	.....	.....
78.21	-194.99	-318.98	.....	0.699	.....	.....
80.5	-192.7	-314.9	.....	.....	.....	0.800
83.2	-190	-310	.....	.....	0.778	.....
181.3	-81.9	-115.4	5.318	.....	.....	1.917
195.1	-78.1	-108.6	.....	.....	.....	.....
234.0	-39.2	-38.6	7.188	.....	.....	5.46
273.1	0	32.0	9.065	.....	8.71	9.95
<hr/>						
			Basic O H. Iron—		Electrolytic Iron—	
			Meyer	Ingot Iron, Powell	Burgess and Kelberg	Ribbeck
213.1	0	32	.....	9.6	8.8	8.9
373.1	100	212	.....	15.39	15.49	14.6
473.1	200	390	.....	23.69	22.6	21.7
573.1	300	570	.....	34.15	31.4	30.8
673.1	400	750	.....	47.80	43.1	41.7
773.1	500	930	.....	62.35	55.3	54.5
873.1	600	1110	.....	79.55	69.8	68.1
973.1	700	1290	.....	103.3	92.9	90.2
1073.1	750	1380	.....	113.2	105.1	103.5
1173.1	800	1470	.....	118.6	111.0	109.9
1273.1	900	1650	.....	121.2	117.8	115.0
1373.1	950	1740	.....	.....	.....	.....
1473.1	1000	1830	.....	.....	.....	.....
<hr/>						
1273.1	950	1740	.....	.....	.....	.....
1373.1	1000	1830	.....	.....	.....	.....
<hr/>						
					Swedish Iron, Honda and Simidu	
					.....	13.2
					.....	20.1
					.....	27.4
					.....	36.0
					.....	46.2
					.....	58.3
					.....	72.0
					.....	86.8
					.....	98.2
					.....	109.5
					.....	109.9
					.....	117.0

Table XII

Temperature Coefficient of Resistivity of Iron at Elevated Temperatures

Investigator	Year	Material	Temperature coefficient of resistivity $\times 100$										
			0-100°C. (32-210°F.)	100-200°C. (210-390°F.)	200-300°C. (390-570°F.)	300-400°C. (570-750°F.)	400-500°C. (750-930°F.)	500-600°C. (930-1110°F.)	600-700°C. (1110-1290°F.)	700-800°C. (1290-1470°F.)	800-900°C. (1470-1650°F.)	900-1000°C. (1650-1830°F.)	1000-1100°C. (1830-2010°F.)
Morris	1897	Transformer iron	0.63	0.77	1.02	1.03	1.21	1.41	1.61	1.88	0.83	0.36	0.21
Niccolai	1908	Kahlbaum iron	0.56	0.68	0.83	1.00							
Somerville	1910	Soft iron	0.57	0.79	1.00	1.23	1.42	1.55	1.89	2.50	0.65	0.46	0.53
Meyer	1911	Kahlbaum iron	0.821	1.11	1.22	1.33	1.53	1.93	2.38	1.31	0.39	0.29	
Meyer	1911	Basic open hearth ingot iron	0.607	0.87	1.10	1.42	1.52	1.80	2.48	1.60	0.27	0.13	
Meyer	1911	Electrolytic iron	0.657	0.78	0.98	1.20	1.44	1.53	2.34	1.93	0.73		
Burgess and Kellberg	1915	Electrolytic iron	0.635	0.83	1.02	1.24	1.45	1.71	1.96	2.15	0.66	0.25	
Holborn	1919	Electrolytic iron	0.66	0.83	1.02	1.81	1.41						
Ribbeck	1926	Electrolytic iron	0.64	0.85	0.99	1.11	1.42	1.63	1.96	2.26	0.90	0.33	
Powell	1934	Basic open hearth ingot iron	0.56	0.79	0.92	1.22	1.27	1.51	1.79	1.93			

Effect of Mechanical and Thermal Treatment—Cold working increases the resistivity, but reannealing of cold worked iron lowers the resistivity to its initial value. Bardenheuer and Schmidt found practically no change in resistivity of electrolytic iron cold drawn various amounts up to 95% reduction in area, but

Tammann and Moritz obtained a maximum increase in resistivity of about 5.7% by cold working 99.8%. Annealing at 600°C. (1110°F.) restored the iron to its original resistivity. Fig. 12 is taken from the work of Tammann and Moritz.

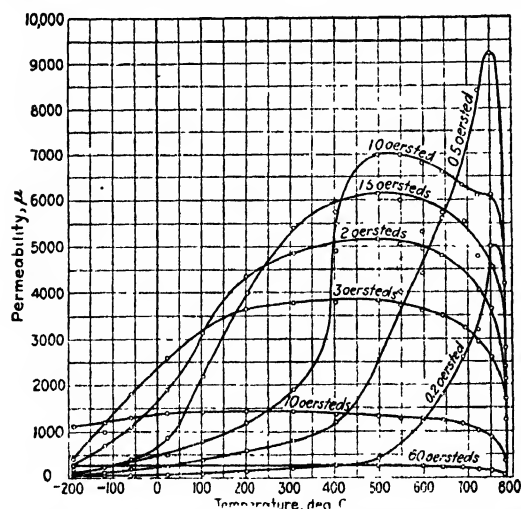


Fig. 16—Variation of the permeability of annealed electrolytic iron with temperature. (Terry.)

Effect of Hydrostatic Pressure—Beckman found the pressure coefficient of electrical resistivity of Swedish iron of low purity (fundamental coefficient of 0.0048) to be 27.4×10^{-7} per atmosphere between 425 and 2097 atmospheres at 0°C. ($\alpha = 1/R \times dR/dP$). Bridgman measured the pressure coefficient on basic open hearth iron (fundamental coefficient = 0.0062) and obtained 24.9×10^{-7} per atmosphere at 0°C. and zero pressure and 21.9×10^{-7} per atmosphere at 0°C. and 12400 atmospheres.

Thermoelectrical Properties—

Table XIII gives the thermal electromotive force produced by bimetallic couples of iron and other metals. The values are in millivolts and are considered positive if the current flows from the iron to the other metal at the junction which is at 0°C. The data were obtained in some cases on samples of unknown

Table XIII

Thermoelectric Properties of Iron Against Other Metals ("Cold End" at 0°C)

Note: Values are given in millivolts and are positive when current flows from the iron to the other metal at the junction which is at 0°C.

Temp.— °C.	Temp.— °F.	Aluminum (Dannecker)	Constantan (I.C.T.)	Copper (Dannecker)	Lead*	Nickel (Dannecker)	Tin (Smits and Spuyman)
-250	-418	....	....	....	-3.35	....	.....
-225	-373	....	....	....	-3.2	....	.....
-200	-328	....	....	-2.2	-2.9	-3.5	.....
-175	-283	....	....	....	-2.5	....	.....
-150	-238	-1.75	....	-1.5	-2.2	-5	.....
-125	-193	....	....	....	-1.75	....	.....
-100	-148	-1.25	....	-1	-1.3	....	.....
-75	-103	....	....	....	-0.9	....	.....
-50	-58	-0.6	....	-0.5	-0.5	-3	.....
-25	-13	....	....	....	0	....	+1.30 (140°C.)
0	32	0	0	0	+0.4	....	+1.31 (150°C.)
25	77	....	....	....	+0.75	....	+1.34 (160°C.)
50	122	....	....	+0.5	+1.2	0	+1.38 (170°C.)
75	167	5.3	+0.95	....	+1.4	....	+1.43 (180°C.)
100	212	+1.25	10.8	+1.45	....	+3	+1.53 (190°C.)
200	392	2.25	16.3	+1.45†	....	+6	+1.7 (200°C.)
300	572	2.8	21.8	+1	....	9	+1.76 (210°C.)
400	752	3	27.6	+0.2	....	10.5	.....
500	932	2.85	33.1	-0.7†	....	11.8	.....
600	1112	....	39.2	-1.5	....	13.5	.....
700	1292	....	45.4	-2.15	....	15.5	.....
800	1472	....	51.7	....	....	18	.....
900	1652	....	57.9	....	....	20	.....
1000	1832	....	....	....	....	22.5	.....
1100	2102	....	+0.7	....	....	25	.....

*Taken from plot of International Critical Tables, I. C. T. formula and data of Dewar and Fleming and Wietzel.

†Inversion point 527.5°C.

‡Neutral point 247°C.

purity and would not be exactly duplicated on other specimens but are given as an indication of the magnitude of the thermoelectromotive forces produced.

Electrochemical Equivalent—This constant is computed from the atomic weight and the valence and there are therefore two values for iron: 0.1929×10^{-3} g. sec.⁻¹ ampere⁻¹ for trivalent iron and 0.2893×10^{-3} g. sec.⁻¹ ampere⁻¹ for bivalent iron.

Magnetic Properties—The magnetic properties, like the electrical are quite sensitive to small changes in treatment and amount of impurities. Samples of high purity iron prepared by long time hydrogen annealing just under the melting point have furnished new and interesting values for the magnetic properties of iron, but the concomitant effect of large grain size no doubt is also present and the results are included here with the caution that grain size may become of increasing influence on the magnetic properties as the purity increases.

Fig. 13 shows hysteresis loops of ingot iron and hydrogenized iron as determined by Cioffi, while magnetization curves for these materials are illustrated in Fig. 14. The permeability of the hydrogenized iron (0.005 C, 0.028 Mn, 0.004 P,

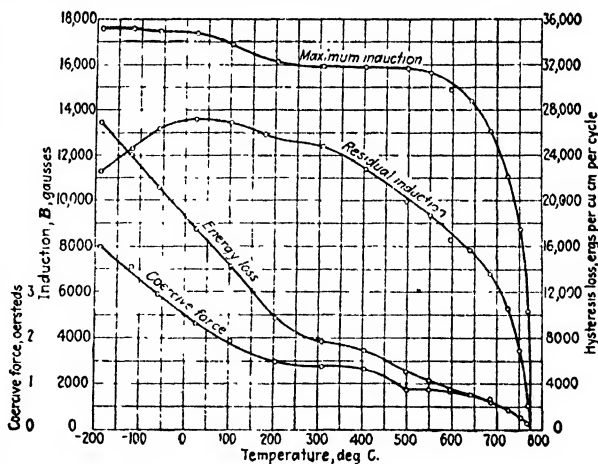


Fig. 17—Variation of the hysteresis constants of annealed electrolytic iron with temperature. (Terry.)

0.003 S, 0.0012 Si, 0.003 O, 0.0001 N₂) is enormously greater at low inductions than irons of commercial purity, but the difference fades out at higher inductions. This is shown in Fig. 15.

Effect of Temperature—In studying the effect of temperature on permeability of Burgess' electrolytic iron, Terry found that this depended on the field strength as shown in Fig. 16. His results on the effect of temperature on the hysteresis constants are given in Fig. 17.

Effect of Grain Size—The work of Sizoo on electrolytic iron (0.024 C, 0.012 S, 0.014 Si) is shown in Fig. 18, while that of Yensen and Ziegler is given in the following equations:

Coercive force = H_c (oersteds).

Hysteresis loss = W , ergs/cm.³/cycle.

Minimum reluctivity = ρ_{min} (thousandths).

For carbon less than 0.002%.....	$\rho_{min} = 0.34 \times 10^{-8} N$ $H_c = 0.0018 N$ $W = 56 N$
For carbon 0.002-0.004%.....	$\rho_{min} = 0.21 \times 10^{-8} N$ $H_c = 0.00114 N$ $W = 34.4 N$
For carbon 0.004-0.008%.....	$\rho_{min} = 0.46 \times 10^{-8} N$ $H_c = 0.0025 N$ $W = 75 N$

Where N is the number of grains per sq.mm.

The effect of orientation, no doubt, is present in the case of the larger grain sized specimens, but does not seem to have been considered by the investigators quoted.

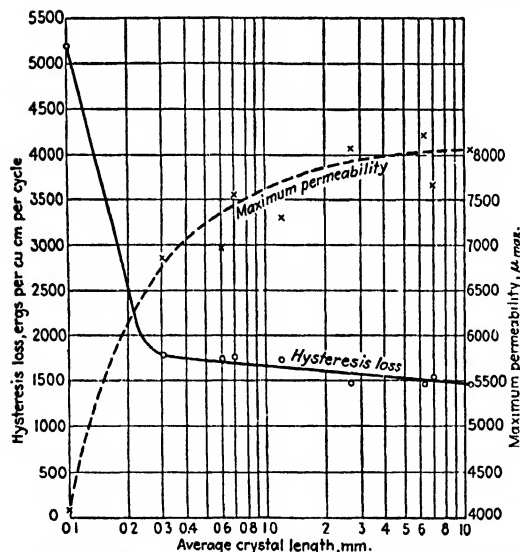


Fig. 18—Effect of grain size of electrolytic iron on hysteresis loss and maximum permeability. (Sizoo.)

Effect of Cold Work—Cold working has a deleterious effect on the magnetic properties of iron. The effect of various amounts of cold reduction on the hysteresis loop of electrolytic iron (polycrystalline) as determined by Gries and Esser is shown in Fig. 19. Cleaves and Thompson state that cold working decreases permeability and increases residual induction, coercive force, and hysteresis loss and leaves only the saturation intensity unaffected.

Optical Properties—Emissivity determinations on high purity iron are rare and even when specimens of such material have been used the experimental procedure has often affected the purity, as when the source of heat was an arc between carbon electrodes. The best accepted values are those of Burgess and Waltenberg in Table XIV, determined with a micro pyrometer:

Table XIV
Emissivity of Iron at Various Temperatures

State	Temp., °C.	Emissivity, %
Solid	1050	37.9
	1350	37.2
	1450	38.3
	1530	38.0
Liquid	1535	38.5
		Average 38.8

The above values are all for $\lambda = 0.65 \mu$ and the average should probably be rounded to 37%.

Emissivity values for iron and steel as measured in various industrial operations may differ from this due to oxide on heated surfaces of solid metal and

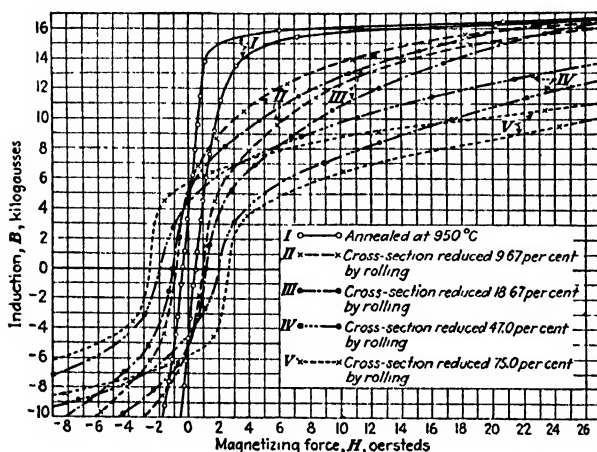


Fig. 19—Effect of cold work on the hysteresis loop of polycrystalline electrolytic iron. (Gries and Esser.)

seem to have been the subject of investigation. Fig. 20 presents the combined results of several workers.

X-ray absorption data have been summarized by Compton from values published by Allen, Hewlett, Ahmad, Ishino, Richtmyer and Warburton, Bragg and Pierce, Martin, and Barkla. Compton's selected values are given in Table XV.

Table XV
X-Ray Absorption for Iron

Wave Length Microns	Compton's Selected Values	Wave Length Microns	Compton's Selected Values
0.017.....	0.058	0.500.....	14.3
0.057.....	0.08	0.600.....	23.3
0.080.....	0.232	0.700.....	36.3
0.100.....	0.265	0.800.....	51.7
0.125.....	0.399	0.900.....	69.6
0.150.....	0.572	1.00.....	95
0.175.....	0.79	1.10.....	128
0.200.....	1.07	1.32.....	220
0.250.....	1.93	1.40.....	270
0.300.....	3.18	1.76.....	60
0.350.....	4.94	1.93.....	67
0.400.....	7.17	2.25.....	104

Gamma Ray Absorption—The minimum apparent coefficient of absorption of gamma rays is as follows:

	100 (μ'/ρ)
Th — C''.....	3.28
Ra — C.....	3.99
Ms — Th ₁	4.15
U — X ₃	4.72

Index of Refraction—The index of refraction depends on the wave length of the incident light. Of the results obtained by numerous investigators, those of Ingersoll seem the most reliable and are as follows:

λ in m μ	228	400	500	700	1000	2000	2250
n	1.30	1.68	2.09	2.73	3.19	4.02	4.14

floating slag on liquid metal. Cleaves and Thompson state that values between 40 and 45% for liquid metal or solid metal with a bright surface and as high as 90% for solid metal with an oxidized surface have been reported. The International Critical Tables, v. V, p. 244, gives the total emissivity for oxidized surfaces of steel as 79% at 200°C., 78.8% at 400°C., and 78.7% at 600°C.

The *reflectivity* determinations found in the literature are for the most part on iron of unknown composition. Moreover, the effect of impurities on this property does not

Mechanical Properties—Elastic Constants—Abram found ingot iron and mild steel have a slightly higher Young's modulus than medium and high carbon steel. They reported 30.1×10^6 psi. for ingot iron and considered that for pure iron in the annealed condition the value would be about 30.2×10^6 psi. Goens and Schmid determined Young's modulus for different directions in a single crystal of ingot iron and found it was more than twice as great in the [111] direction as in the [100] direction.

$E [100] = 19,000,000 \text{ psi. (13,500 Kg./sq. mm.)}$
 $E [111] = 41,000,000 \text{ psi. (29,000 Kg./sq. mm.)}$

Kimura and Ohno report the values in Table XVI for the elastic constants for single crystals of iron.

Table XVI
Elastic Constants for Iron (Single Crystals)

	[100]	[110]	[111]
Young's modulus, psi.....	18.9×10^6	31.3×10^6	40×10^6
Modulus of torsion, psi.....	16.1×10^6	9.6×10^6	8.5×10^6
Bulk or Voigt's modulus, psi.....	$S_{11} = 10.9 \times 10^6$	$S_{12} = -4.7 \times 10^6$	$S_{44} = 14.7 \times 10^6$
Elastic constants, psi.....	$C_{11} = 39.4 \times 10^6$	$C_{12} = 24 \times 10^6$	$C_{44} = 18.2 \times 10^6$

Other values reported for polycrystalline irons are 29,300,000 psi. for ingot iron as determined by Kenyon; 29,600,000 and 30,600,000 psi. for electrolytic iron as reported in the International Critical Tables and Grüneisen, respectively; and 29,400,000 psi. for carbonyl iron as given by Duftschmid, Schlecht and Schubardt.

Values for the modulus in torsion or shear modulus on polycrystalline irons are as follows:

Shear Modulus in Psi.

Ingot iron.....	11.77×10^6
Ingot iron.....	11.78×10^6
Electrolytic	11.45×10^6
Electrolytic	11.81×10^6
Electrolytic	11.66×10^6

Poisson's Ratio is generally considered to lie between one-fourth and one-third for most metals and is given for iron as 0.28 in various handbooks.

Compressibility—The compressibility of iron has been studied by various investigators, but the outstanding work in this field is that of Bridgman, who determined the compressibility of ingot iron. Cleaves and Thompson have summarized his findings and state that at 30°C. the mean compressibility between 0 and 10,000 kg. per sq.cm. was 0.566×10^{-6} kg. per sq.cm. and at 75°C. it was 0.572×10^{-6} kg. per sq.cm. over the same range of pressure. The pressure coefficient for this range of

pressure was 7.0×10^{-6} per kg. per sq.cm. and the temperature coefficient was 2.3×10^{-4} per °C. over the range of 30-75°C.

Adams found the compressibility of a specimen of Yensen high purity iron agreed with that of Bessemer steel within 1 part in 500 over a range of 0-7000 kg. per sq.cm. pressure.

Compression, Tensile, Fatigue, Impact, and Hardness—These values for polycrystalline irons at room temperature are given in Table XVII. The data presented are of necessity only a summary of selected values.

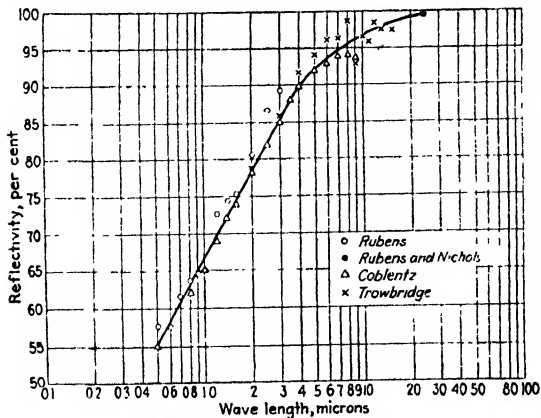


Fig. 20—Reflectivity of Iron.

Table XVII

Compressive, Tensile, Torsion, Fatigue, Hardness, and Impact Values of Iron

	Ingot Iron					Forgings			
	Hot Rolled Rods or Plates	Annealed Rods or Plates	Normalized	Dead Soft	Cold Worked (Approx. Max.)	Finished Cold	Finished Hot	Finished Hot, Annealed*	Finished Hot, Quenched, 1725°F., Water
Compression—									
Elastic limit.....		19,400							
Proportional limit..		19,200							
Yield strength.....		20,800							
Tensile—									
Yield strength.....	26,000–32,000			19,000	*	26,900	19,100	18,300	30,300
Tensile strength....	42,000–48,000			38,500	100,000	43,800	42,200	41,000	47,000
% elongation.....	22–28			43–48		41.8	44.7	47.0	36.2
Gage length, in....	8			2		2	2	2	2
% reduction of area	65–78			70–77	65–70	75.6	77.3	70.6	70.0
Torsion—									
Proportional limit..	12,000–15,000								
Yield strength.....	14,000–23,000								
Hardness—									
Brinell Hardness No.	82–100			67	220	101	90	82	110
Rockwell B	39–55								
Scleroscope									
Fatigue—									
Reversed bend.....		26,000 ^b							
Reversed torsion...		12,800							
Axial stress.....		26,700							
Impact—									
Charpy, kg-m.....	0.9 ^d	2.66 ^d							
Izod, ft-lb.....		90.0 Long.							
		56.3 Trans.							

	Electrolytic Iron		Hydrogenized Iron	Carbonyl Iron
	As Deposited	Fused and Annealed		
Compression—				
Elastic limit
Proportional limit
Yield strength
Tensile—				
Elastic limit
Proportional limit
Yield strength	10,000–20,000	7,000	15,000–24,000
Tensile strength	55,000–113,500	35,000–40,000	14,000	28,000–40,000
% elongation	25–3	40–60	.....	30–40
Gage length, in.....	2	1.5	.....	L = 10d
% reduction of area.....	70–90	.....	70–80
Torsion—				
Proportional limit
Yield strength
Hardness—				
Brinell Hardness No.....	{ 140 350	45 90	.....	.....
Rockwell B	B-10–B10	.....
Scleroscope	56–80
Fatigue—				
Reversed bend
Reversed torsion
Axial stress
Impact—				
Charpy, kg-m.....	21.2°	.....	.....
Izod, ft-lb.

*25 hr. at 1650°F. slow cool.

*Cold worked iron has no sharp yield point. The stress corresponding to the arbitrarily chosen strain of 0.5% on a 2 in. gage length can be distinguished up to about 15% cold reduction beyond which this value coincides with the tensile strength.

*33,000 psi. after water quench from 1500°F.

*Annealed electrolytic iron. Tested at 20°C. Type of specimen, probably large Charpy.

*Hot rolled ingot iron. Tested at 20°C. Test specimen 60 × 10 × 10 mm.

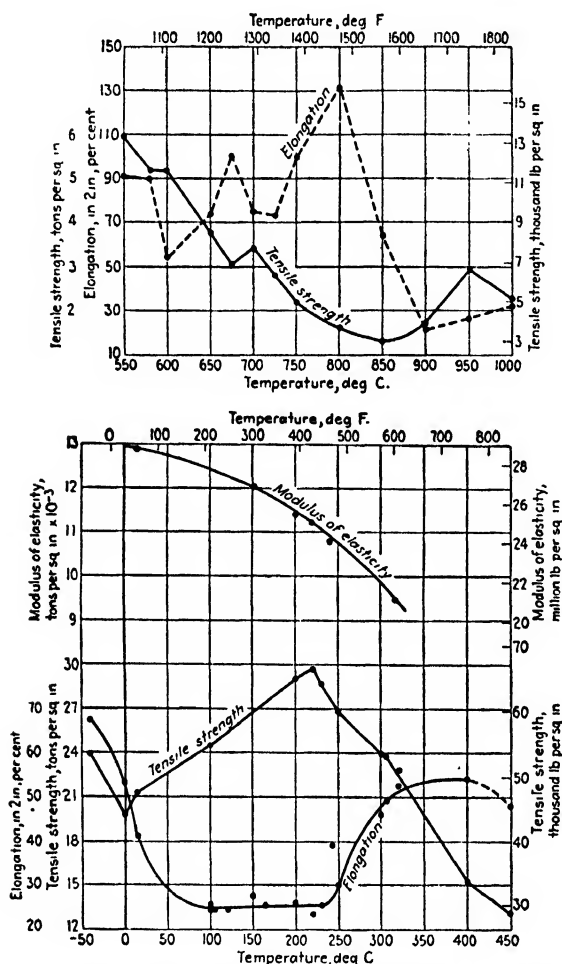


Fig. 21—Tensile properties of ingot iron at various temperatures. (Lea.)

Table XVIII
Tensile Properties of Ingot Iron at Elevated Temperatures
Short Time Tests

Temp., °C.	Tensile Strength, psi.	% Elongation Including Fracture $L = 4 \sqrt{\text{Area}}$	% Reduction of Area	Modulus E
18	49,500	45	69	29,800,000
100	57,800	27	61.5	29,250,000
150	59,800	26.5	60	28,400,000
200	65,600	26.5	54	27,800,000
250	64,700	30.0	54	27,200,000
300	62,500	38.5	56	26,500,000
350	56,700	44.5	61	25,800,000
400	44,800	51	67.5	25,000,000
450	37,000	51	67.5	24,000,000
500	27,100	49	63.5	.....
600	15,200	34	49.5	.....
700	9,200	53.5	55.5	.....

Effect of Temperature on Mechanical Properties—Although variations in testing technique affect the results at room temperature, they have an even greater effect at high and low temperature. Speed of testing, shape of test piece, method of gripping, uniformity of temperature, and accuracy of temperature measurement are important factors, which, unfortunately, are frequently not mentioned in many reports of tests found in the literature.

Results obtained at elevated temperature may be divided into two groups: "Short time" and "creep." Tapsell and Clenshaw give the results shown in Table XVIII for ingot iron when using a Martens extensometer for determining the modulus at elevated temperatures. The loading was applied in steps. Total time to proportional limit about 20 min. Normalized bars 2 in. gage length and $\frac{1}{2}$ in. dia.

The work of Lea covered the temperature range of -40 – 1000°C . and in general his tensile values are lower than those of Tapsell and Clenshaw, and above the "blue brittle" range the elongation is greater. These results are shown in Fig. 21.

The maximum in tensile strength in the proximity of 200°C. is generally ascribed to the so-called "blue brittle" phenomenon. The temperature at which this maximum tensile strength occurs depends on testing speed; slower speeds throw it to lower temperatures, and if the test is made sufficiently slow (two months) at room

temperature, a strength is obtained approximately equal to that obtained at ordinary rates of testing in the "blue brittle" range.

The "creep" strength is considerably lower than the tensile strength determined in the short time test. The value obtained depends on the rate of creep chosen. Tapsell and Clenshaw have determined the strength of ingot iron at various rates of creep as shown in Fig. 22. The rate of creep used for curve 1 is less than 1×10^{-4} in. per day.

Mechanical Properties of Single Crystals
—Osmond and Frémont determined the yield strength in compression to be 19,800 psi. on cube faces and 24,200 psi. on

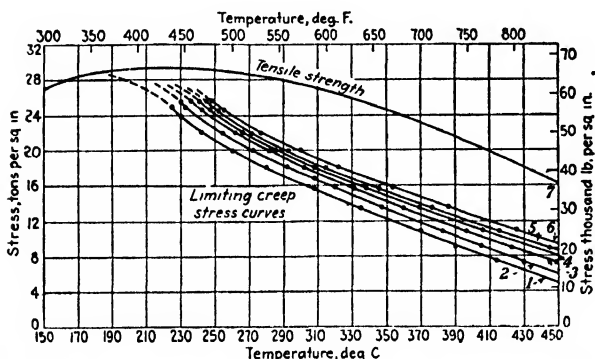


Fig. 22—Creep strength of ingot iron. (Tapsell and Clenshaw.)

Curve	Stretch, in.	Time, Days
1	Limiting creep-stress	
2	0.001	300
3	0.005	60
4	0.010	25
5	0.025	8
6	0.075	2-3
7	Gives the tensile strength	

octahedral faces of single crystals prepared from a decarburized steel rail (0.06 C, 0.30 Mn, 0.116 P, 0.02 S, 0.051 Si). This same material had a tensile strength of 39,500 psi. and a yield strength of 23,500 psi. perpendicular to a cube face and a reduction of area of 85%.

Edwards and Pfeil prepared single crystals from mild steel and found tensile strength values from 21,000-34,500 psi. on ten different crystals (orientations not determined); yield strength 4,300-5,600 psi.; elongation in 2 in. 30-54%; and Young's modulus $22.4-29.8 \times 10^6$ psi.

Osmond and Frémont's Brinell hardness results on above-mentioned specimen after annealing at 550°C. were 75 on cube face, 79 on dodecahedral face, and 81 on octahedral face. After annealing at 800°C. the corresponding values were 66, 69, and 76. Pfeil found on his single crystals a Brinell hardness of 80, which was the same in different directions of the crystal within the limit of accuracy of the test.

Effect of Grain Size on Mechanical Properties—Table XVIII-A gives the variation in tensile properties with grain size as determined by Edwards and Pfeil. Pomp found the Brinell hardness only slightly affected by grain size and reported the following: Brinell hardness 83 for 68 grains per sq.mm.; 87 for 827; 89 for 1350; 96 for 2310; and 95 for 3970 grains per sq.mm.

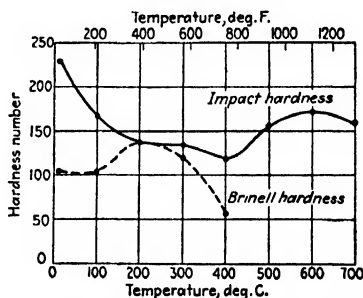


Fig. 23—Hardness tests on ingot iron. (Tapsell and Clenshaw.)

Table XVIII-A
Effect of Grain Size on Tensile Properties of Iron*

Specimen No.	Grain Size, Grains per sq.mm.	Tensile Strength, psi.	Yield Strength,† psi.	Elongation in 2 in., %
Series 1				
1	9.7‡	23,900	5,900	28.8
2	7 ‡	26,200	5,600	30.5
3	2.5‡	30,600	6,400	39.5
4	6.3	33,700	6,500	35.3
5	15.3	36,600	6,200	47
6	35.6	38,200	8,300	48.8
7	48.8	38,300	9,400	50.7
8	51	38,900	10,000	44.8
9	75.5	42,000	20,100	47
10	77.5	41,600	20,200	48.3
11	91.6	40,000	16,600	50.3
12	92	40,300	18,800	50
13	120	41,200	16,700	42.5
14	130	41,600	15,700	41.3
15	194	41,900	15,400	47.5
Series 2				
1	27	38,500	8,400	41.3
2	34	39,300	10,500	41.3
3	53	38,600	7,700	46.3
4	57	38,000	10,700	38.8
5	78	38,500	11,300	33.5
6	84	39,600	12,100	51.3
7	98	42,300	14,700	46
8	98	43,100	15,500	46.5
9	102	42,600	16,300	44.8
10	108	44,400	15,800	46.3
11	109	42,800	15,100	42.8
12	113	42,200	14,500	47.8
13	118	43,100	18,000	48.5
14	127	43,200	19,500	44
15	135	43,300	22,200	45.3
16	157	44,200	22,600	45.3
17	168	38,100	15,700	45
18	203	38,200	14,200	44.8
19	230	37,700	13,800	48
20	245	37,300	14,000	45.5
21	307	39,100	13,800	48.3

*Edwards and Pfell.

†Reported as proportional limit.

‡Diameter of average crystal in mm.

Torsion Tests at Elevated Temperatures—Tapsell and Clenshaw determined the torsional strength of ingot iron at elevated temperatures by means of short time tests of a duration of about 20 min. up to the proportional limit and 20 min. from the proportional limit to fracture. The results are given in Table XIX.

Table XIX
Torsional Properties of Ingot Iron at Elevated Temperatures

°C	Modulus of Rupture	Modulus of Rigidity	Angle of Twist per in. at Fracture, Degree
16	63,200	11,600,000	778
100	66,100	11,500,000	632
150	70,300	11,400,000	628
200	68,300	11,200,000	479
250	68,300	11,100,000	447
300	69,000	11,000,000	406
350	65,900	10,700,000	297
400	51,700	10,500,000	336
450	41,000	10,300,000	326
500	25,100	.....	249
600	15,000	.....	285

Hardness at Elevated Temperatures—Both dynamic and static hardness tests have been made on ingot iron by Tapsell and Clenshaw as shown in Fig. 23. O'Neill determined the scratch hardness at various temperatures of a carbon-free iron made by decarburizing a mild steel in hydrogen. These results are shown in Fig. 24. The hardness values are taken as the resistance to the production of a scratch 0.1 mm. wide at various temperatures.

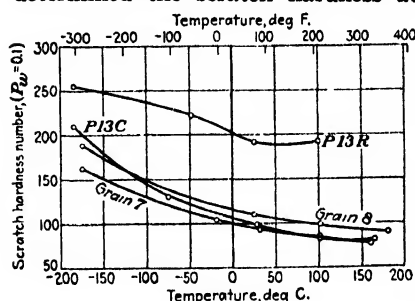


Fig. 24—Change in scratch hardness with temperature. P13R—A cold rolled polycrystalline carbon-free iron, Mn 0.44%; Si 0.02%; S 0.028%; and P 0.020%. P13C same as P13R, but annealed. Grain 8 and Grain 7, two single-crystal grains, the scratch on No. 8 being in the [110] direction on a (100) face.

Hardness at Low Temperatures—The hardness of Swedish iron has been reported by Dewar and Hadfield and DeHaas and Hadfield as 101 at 15°C., 230 at -182°C., and 232 at -253°C., while Guillet and Cournot found the hardness of electrolytic iron to be 80 at +20°C., 77 at -20°C., 77 at -80°C., 95 at -110°C., and 269 at -182°C.

Alternating Stress Tests at Elevated Temperatures—Alternating stress tests on Haigh alternating stress machine at 2,400 cycles per minute with equal plus and minus stress on a basis of 10^7 reversals gave the following results:

°C.	Estimated Limiting Range of Fatigue Stress, psi.
18	28,700
100	24,000
200	25,500
300	33,400
400	28,900
500	12,300

Solubility of Hydrogen in Molten Iron

°C.	Volume of Hydrogen in cc. per g. of Iron (Standard Conditions)
1530 (M.P.)	0.272
1550	0.279
1650	0.310

Permeability of Iron to Hydrogen at Various Temperatures

°C.	Permeability
200	0.83
300	5
400	25
500	100
600	336

Permeability is the value of K in the equation $\frac{dm}{dt} = -K_{p_0} \frac{\Delta p}{\Delta z} dx dy$ where dm

is the mass of gas passing in direction z in time dt through a diaphragm of the solid of area dx dy and thickness Δz , the difference in pressure on the two sides of the diaphragm being Δp ; the minus sign indicates the flow is in the direction of decreasing pressure. p_0 is the density of the gas at zero C. and pressure of 1 atmosphere; dm/p_0 is the volume of dm at zero and 1 atmosphere.

p is expressed in atmospheres.

K is expressed in 10^{-6} cm³ per atm-sec.

Plastic Deformation of Iron

By C. H. Mathewson*

Block Movements of Slip and Twinning in the Crystal Lattice of Iron—Iron in common with other metals accommodates itself to plastic deformation by the gliding of crystal blocks or lamellae on one another, and this process ordinarily becomes one of pure translation in which the orientation of the crystal changes only as the gliding along planes cutting across the axis of stress application sets up a bending moment around an axis in the slip plane at right angles to the direction of slip. It is this bending or twisting of crystals and parts of crystals that gives rise to the preferred orientations or textures found in wrought metal. Such effects are important, as the physical properties of the metal are determined in large part by the orientation of its particles. The state of purity has a remarkable effect on the force necessary to start translation, or keep it in action, and in general on the dynamics of the process. As a principle of guidance it may be said that translation starts when the shear stress on a competent slip plane in a possible slip direction rises to a critical value, but, as the simple slipping process brings about change of orientation, the resolved shear stresses change and slip on one family of planes may soon be accompanied or replaced by slip on another family. In single crystals the normal outcome of the process may be fairly well predicted but in ordinary polycrystalline metal the mutual interferences among the grains lead to complications and there is no clearly accepted method of rationalizing the textures formed in such material by the translation process.

X-ray studies have revealed the general characteristics of textures¹ formed during the different industrial processes of working iron (and other metals), as indicated in a later paragraph, but it must be realized that data of this character give merely a rough indication of the preferred orientations of the crystals; as considerable deviation from any stated orientation always occurs, and the texture changes from one point to another in the object, for example, from surface to center in a drawn wire. It is this variability that renders the study of textures important as a method of controlling the conditions of plastic deformation in developing desirable directional properties in wrought metal for any particular purpose.

The gliding process may also become one of mechanical twinning, which requires that each slip plane shall move the exact fraction of the distance between atoms on the adjacent slip (twinning) plane that will set up anew the crystal lattice pattern in a changed or twin orientation. In iron, this process does not appear to be of great importance, as twin lamellae, or so-called Neumann bands are produced only under certain limiting conditions and do not usually represent the major effect of the plastic deformation. A general understanding of the elements and the simple mechanism of block movements defining the processes of translation or twinning may be obtained from the following outline.

Significant Directions and Planes—At temperatures above 2550 and below 1650°F. crystals of pure iron have their atoms arranged according to the simple body centered cubic pattern as illustrated in Fig. 1 of the article in this Handbook entitled "Physical and Mechanical Properties of Pure Iron".

For the purpose of considering displacements of atoms and planes by plastic deformation of the iron crystal, it is best to orient the body centered cubic unit of structure (Fig. 1) so that one of the body diagonals, *ab*, passing through two corner atoms and the central atom is in a vertical position. This and the other three body diagonals are lines or directions through the crystal along which the atoms make the closest possible approach to one another. When the crystal is forced to change its shape by the action of an external stress the atoms resist separation in these close packed strings and shearing occurs by some form of block movement in one or another of these four significant directions [111]. If we imagine other unit cells grouped around the first in Fig. 1, it is clear that the atom at each corner of the original cell belongs to a close packed string including the central atom of a respective neighboring cell. Similarly, the outlying corner atoms of these new cells belong to close packed groups derived from more

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¹All references are given at the end of this article.

distant cells. Using the central string of atoms as an axis, a vertical plane may be rotated into various positions such as, a $c' b d'$, which is designated as a plane of form $\{110\}$, and the other shaded position designated $\{112\}$. Each plane furnishes some characteristic spacing of these close packed strings of atoms and some characteristic geometrical relationship between the atoms in this plane and those in a parallel plane passed through adjacent strings of atoms. These details can be studied in some form of a projection such as the one given in Fig. 2 in which all atoms are projected vertically into a plane of the form $\{111\}$ at right angles to the close packed string, ab (body diagonal), shown in Fig. 1.

It is evident in Fig. 1 that the atoms of the three different strings originating at a, c and d do not match one another in horizontal planes, while those originating at c, c' and c'' or at d, d' and d'' meet this condition perfectly.

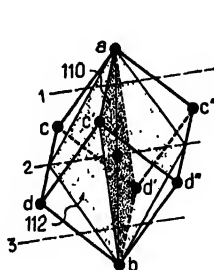


Fig. 1

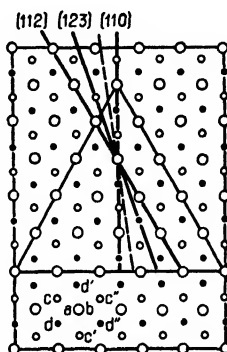


Fig. 2

Fig. 1—Body Centered Arrangement of Atoms with a Cube Diagonal in Vertical Position. 1, 2, 3, Body Centered Atoms From Adjacent Cells Occur at Each of These Levels.

Fig. 2—Projection of Atoms of Body Centered Cubic Lattice in a Plane Perpendicular to Close Packed Strings of Atoms (an Octahedral Plane). Atoms in the Plane of the Projection and 4th and 7th Planes Above Shown by Large Circles; in the 2d, 5th and 8th Planes by Smallest Circles; and in the 3d, 6th and 9th by Circles of Intermediate Size.

These differences in level are indicated in the projection of Fig. 2 by using circles of different sizes, with letters indicating the proper relationship to Fig. 1. A projection of this sort is of course competent to represent an indefinitely large number of unit cells piled on and around one another according to the plan of orientation selected. Planes of particular significance or interest may be selected for boundaries and in this projection (Fig. 2) dodecahedral planes $\{110\}$ of Fig. 1 are chosen for right and left-hand boundaries and trapezohedral planes $\{112\}$ of Fig. 1 for the upper and lower boundaries.

Within the figure it would be possible to draw many sets of parallel lines, bringing the projected strings of atoms into planes of various kinds. Thus a set of lines parallel to the vertical boundaries would represent the closest possible grouping of the strings into (dodecahedral) planes and inspection of the figure shows that there are two other sets of planes inclined 60° to the first set having these same characteristics.

Slip Planes and Directions—The common condition that plastic deformation of a crystal occurs in the direction of a line of closest atom packing by block movement along planes of the densest atom packing on which the stress intensity has reached the highest value would, in the case of a polished iron crystal oriented to correspond with Fig. 2 and loaded with maximum stress intensity in the direction of the atom strings (that is, perpendicular to the plane of the projection), cause one or more sets of slip bands to appear parallel to the most severely stressed dodecahedral planes. Actually, the slip bands observed in iron are of a more complex character, often irregular, forked or wavy and apparently unrelated to any principal plane of the crystal. O'Neill¹ and Pfeil² have observed bands parallel to planes of the form $\{112\}$ (horizontal boundaries in Fig. 2). Taylor and Elam³ emphasize the importance of the close packed atom strings in guiding the *direction* of slip, but consider the block movement to occur not along planes of simple indices but in

rod like bundles of atom strings whose boundaries are determined by stress considerations alone. Gough,⁶ in an elaborate analysis of the deformation of a single crystal of iron stressed in torsion, concludes that slip may occur in the direction of the close packed atom strings on quite a variety of planes containing these gliding elements, that is, planes of the form $\{110\}$, $\{112\}$, or $\{123\}$. These are the planes some of whose projections are shown by the lines drawn in Fig. 2. If the shear stress resolved in the direction of the close packed atom string is greater on one of the designated crystallographic planes than on any other conceivable plane, slip is likely to occur on the planes of this set without further complication. However, if the maximum shear stress occurs on some intermediate plane corresponding to the dotted line of Fig. 2, slip will occur on particular planes of the above designated forms located on both sides of the plane of maximum resolved shear stress $\{110\}$ and $\{123\}$, in Fig. 2. Under these conditions the slip bands will be of a duplex type with an average slope corresponding to the dotted line of Fig. 2. Fahrenhoust and Schmid⁶, however, considered $\{123\}$ the most probable planes of slip and Sauerwald and Sossinka⁷ found only the traces of these as slip planes after compression at room temperature.

Most recently, Barrett, Ansel and Mehl¹⁰ have verified Gough's general conclusions, but find that in silicon ferrite, either a low temperature or a high silicon content causes slip to be confined wholly to planes of the form $\{110\}$.

Severe Deformation—As the slipping proceeds in any crystal the process tends to become more complicated owing to a rotation which accompanies the block movement and consequent increase of stress in other eligible slipping directions. Large amounts of deformation therefore bring many different slip planes into play and in the case of ordinary polycrystalline material the process is further complicated by inhomogeneity of the force field at the grain boundaries. Hardening accompanies deformation of this character perhaps owing to an increased resistance to slip through the minute blocks of crystalline material which in moving past one another have developed slight differences of orientation (nonuniform curvature or lineal nonregistry at the boundaries).

Preferred Orientation Under Various Forms of Stress—In spite of the complex mechanism of the slipping process the crystalline particles of metal worked into a given form by continued application of stress in some prescribed manner finally become forced into positions closely approximating a definite and characteristic *preferred orientation*⁸. Simple stretching brings a cube face diagonal $[110]$ into the axis of the rod with a radial disposition of a corresponding set of cube edges $[001]$ in the different crystals. In cold drawn wires $[110]$ also occurs as the fiber axis. Under compression⁴ a body diagonal $[111]$ and to a lesser extent a cube edge occurs in the direction of compression with a cube face diagonal in the radial position. In torsion the cube face diagonal and to some extent the $[112]$ direction becomes the fiber axis with the body diagonal tangential. Cold rolling brings a face diagonal into the direction of rolling and a cube face into the plane of rolling.

Twinning—Planes of trapezohedral form $\{112\}$, parallel to the sides of the triangle outlined in Fig. 2, have the atoms of their close packed strings at the same level in a given horizontal section. In passing from one to another of these adjacent parallel planes, the strings shift laterally into positions half way between their former positions and vertically so as to bring the atoms either one-third or two-thirds of a full atomic distance above the atoms in the first plane, depending upon the direction of progression. If, beginning with a certain plane, say the one whose projection forms the base of the triangle in Fig. 2, the atoms in the next plane towards the bottom of the figure are brought one-third, instead of the normal two-thirds, of an atom distance above the atoms in the first plane, and the atoms in the third plane two-thirds, instead of the normal one-third, above, the altered region is said to be twinned with respect to the rest of the crystal. This change has been effected in the lower rectangular area which, therefore, constitutes the projection of a twin band.

Twinning by Pure Shear—The mechanical action of pure shear, in which the distance traversed by any particle in the direction of shear is proportional to its distance from the plane of shear, would produce this result, assuming the first plane (base of the triangle) to be the plane of shear and the shearing movement on the next plane to be exactly one-third of the distance between atoms in the close

packed string. This is believed to be the mechanism of mechanical twinning in iron.^{9, 10}

Close observation of Fig. 2 will make it clear that this same structural change may be obtained by shearing along any one of the three families of planes of the form $\{112\}$ represented by the sides of the triangle and that no other twin configuration is possible in this projection. However, since there are three additional body diagonals representing close packed strings of atoms in the iron lattice, three other projections each of them competent to illustrate the formation of a new twin configuration by shear along any one of three additional planes of the form $\{112\}$ are possible.

Infrequency of Twinning in Iron—So many planes are available for deformation by the ordinary process of slip that the much more restricted or specialized form of slip necessary for twinning would be expected to occur only exceptionally in pure iron. Stiffening of the lattice by alloying favors the occurrence of twinning. Somewhat brittle coarse grained ferrite containing silicon or phosphorus twins readily when deformed by impact. Coarse grained Armco iron also twins readily by impact at room temperature. It is reported¹¹ that pure ferrite twins readily even by slow deformation at the temperature of liquid air. Barrett, Ansel and Mehl in their recent investigation¹² of the plastic deformation of iron have demonstrated that twinning, which could be produced in pure iron by slow deformation (torsion) at $-200^{\circ}\text{C}.$, occurs at higher temperatures with increasing silicon content; until, with approximately 5%, it is the favored mechanism of deformation close to room temperature. It is followed in this relatively brittle alloy by cleavage, and then slip on planes of form $\{110\}$ as the temperature is further increased. Even under the most favorable conditions only thin sections of a crystal can be stressed in the exact manner necessary to produce the twin structure. Twinning in iron is therefore observed only in the form of thin lamellae usually called *Neumann bands*.

Deformation of Face Centered Cubic Iron—Ordinary grades of iron and likewise metal of exceptional purity containing only minute traces of the most tenaciously adherent impurities such as oxide, nitride, or carbide, when heated above $1650^{\circ}\text{F}.$, but not above 2550° , have their atoms arranged according to the face centered cubic pattern illustrated in Fig. 1d of the article on Physical and Mechanical Properties of Pure Iron given in this Handbook. (According to a recent accurate determination¹³ the lower A_3 point lies between 1650 and $1675^{\circ}\text{F}.$ in very pure iron). While no detailed study of the slip planes and directions brought into play by hot working pure iron in this range of temperature appears to have been made thus far, there is little doubt that the mechanics of deformation are analogous to those observed in aluminum¹³, copper¹⁴, and other face centered cubic metals.

In wrought and annealed austenitic steels in which iron has been alloyed so as to preserve the face centered cubic arrangement of atoms, the microstructure is strikingly similar to that of the common face centered cubic alloy, alpha brass, even exhibiting the familiar twin bands which are seen in both metals after recrystallization following plastic deformation. This points to a similarity of the deformational process in both cases and the analogy in all probability may be extended to include the behavior of pure iron at elevated temperatures.

Planes and Directions of Slip in the Face Centered Cubic Lattice—In the face centered cubic metals only the planes of closest atom packing, the octahedral planes $\{111\}$, function as slip planes and the slip occurs in the direction of one of the three cube face diagonals representing close packed rows of atoms on the given plane. Four families of octahedral planes are available for this purpose.

In single crystals under tension stress, slip starts on the set of octahedral planes for which the computed shear stress is a maximum, and continues on these planes until rotation of the lamellae brings an equal load on another set of octahedral planes. After a short period of extension by slipping on both sets of planes the crystal usually breaks with a wedge shaped fracture.

Pursuing the analogy with face centered cubic metals still further, hot rolling of iron above $1650^{\circ}\text{F}.$ might be expected to develop preferred orientation of the crystalline particles¹⁵ with the normal to a trapezohedral plane, $[112]$, approximately parallel to the direction of rolling and a dodecahedral plane $\{110\}$ parallel to the plane of rolling. Subsequent cooling below the A_3 point would produce some form of reorientation depending upon the relationship between the two sets of crystal axes established during the transformation. No accurate details of this process are yet available.¹⁶

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Effect of Cold Work on the Properties of Iron

By Reid L. Kenyon* and Robert F. Mehl†

Introduction—The physical and mechanical properties of pure iron are given in another article in this Handbook.¹ The present article deals only with the effect of plastic deformation on these properties. Critical examination of the literature reveals that much of the published data on "pure iron" are actually on low carbon steel, sometimes with as much as 0.10% carbon and 0.50% manganese, besides other impurities. Due to the fact that few, if any, of the properties of pure iron can be extrapolated from such data, they are omitted from this article. While Armco Ingot Iron and electrolytic iron are not pure, they have been taken as such for the purpose of this tabulation. Since the few published results are from isolated tests, it is impossible to discriminate and select "best values." The data given here should be taken only as provisional, and as an indication of the need for further experimental work on the properties of plastically deformed pure iron.

The Effect of Cold Working

The previous mechanical and thermal history of the material, such as internal strain and grain size, has been found to have a marked effect on the response to cold working. Gries and Esser² give the results of Brinell tests on polycrystalline and monocrystalline iron after various degrees of cold rolling. Their values are reproduced in Fig. 1. The method of cold working also affects the results. Wire drawing produces a greater change than rolling for the same amount of reduction. Jeffries and Archer³ give tensile strength values for cold drawn Armco Ingot Iron wire, which are compared in Fig. 2 with cold rolled material. Greulich⁴ also reports the effect of cold rolling on the tensile properties of Armco Ingot Iron, but shows it to be considerably greater than normal, probably owing to a different previous treatment.

Various attempts have been made to express the properties of cold worked metals as functions of the percentage reduction. Greulich⁴ finds these relationships between reduction in thickness and hardness, yield point, and tensile strength to be logarithmic up to a limiting amount of reduction, but Templin⁵ shows that the tensile strength versus per cent reduction of area is a straight line. He gives the following equation for the tensile strength of Armco Ingot Iron: Tensile strength = 37,500 (1 + 1.64 R), where R is the fractional reduction of thickness. Greulich⁴ gives the equation: Tensile strength = 46,000 + 7,510 log. ϕ , where ϕ = the percentage reduction of thickness.

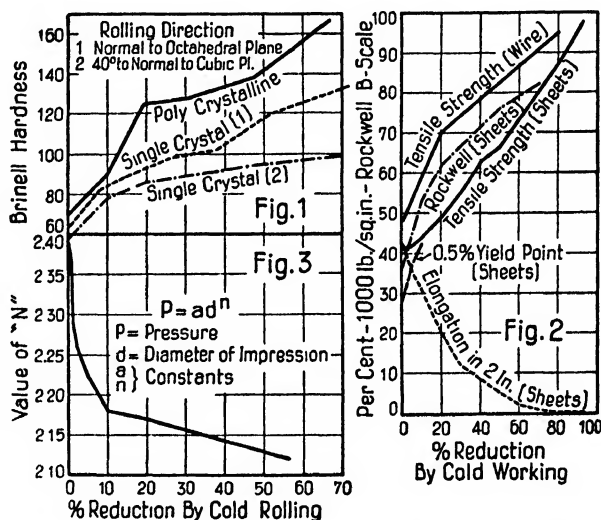


Fig. 1—Effect of grain size and orientation on increase of hardness with cold rolling (Gries and Esser).

Fig. 2—Effect of cold working on the properties of Armco Ingot Iron (test on wire by Jeffries and Archer³ and on sheets by Kenyon and Burns⁴).

Fig. 3—Variation of Meyer's constant "N" with cold rolling.

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¹All references are given at the end of this article.

Templin's formula is believed to be in better agreement with most test data, although it should be remembered that all such particular relationships should be expected to apply only to material in the same initial condition. Their general application to pure iron in all conditions is doubtful.

A work hardening coefficient may be derived from Meyer's equation relating load and diameter of impression in the Brinell hardness test.⁷ In this equation, $p = a \cdot d^n$; the exponent n may be taken as a measure of the capacity of a material to work harden. Fig. 3 shows a series of such values for Armco Ingot Iron¹² cold rolled up to 57%. It will be seen that n decreases with cold work as expected. The slope of the true stress tensile curve is much used in Germany as a measure of rate of work hardening,^{8,9} but doubt has recently been expressed⁴ as to its usefulness, owing to the fact that this slope often is a constantly changing quantity. (See Stead¹⁰ and O'Neill and Greenwood¹¹ for additional studies on true stress curves).

The effect of cold working on the shape of the tensile stress-strain curve for Armco Ingot Iron is shown in Fig. 4. The disappearance of the yield point, increase of the tensile strength, and loss of ductility are the most noticeable effects. The curves in Fig. 4 are for specimens tested immediately after cold rolling; aging at room temperature or at slightly elevated temperatures alters these curves profoundly.¹²

The effect of cold work on the density is given elsewhere.¹ The electrical conductivity and magnetic properties are adversely affected, but no data have been found for high-purity iron.

Structure — The first visible effect of cold plastic deformation on the microstructure of iron is the production of slip bands on a polished surface. If the deformation is carried to a sufficient amount, the grains become distorted and elongated, and this appearance, unlike slip bands, is not changed by repolishing and reetching. This effect can only be detected after considerable cold reduction.

Macroscopically, iron exhibits, on fairly smooth or polished surfaces, a peculiar phenomenon that has been variously designated: Hartmann, Lüders, flow-lines, "worms," and "stretcher strains."^{13, 14, 15} The formation of these markings is associated with the behavior of iron at the yield point (sharp yield point with a definite amount of yield point elongation).⁴ When formed in tension, these markings are surface depressions resulting from local yielding; when formed in compression, they are local elevations on the surface. Deformation does not produce these markings on iron which has been previously cold worked an amount sufficient to prevent a sharp yield point (Fig. 4).

Sudden or impact deformation produces the so-called impact twins or Neumann bands. These twins differ from twins in face-centered metal in that they frequently exhibit irregular or serrated outlines; apparently iron forms no strain-anneal twins.

The mechanical properties of plastically deformed iron change with time after cold deformation when the material is held at room temperatures and at a more rapid rate at slightly elevated temperatures. This is called "aging" and is readily observed from the ordinary physical tests as a progressive increase in yield point, tensile strength, and hardness and decreases in elongation, reduction of area, and notch impact value,^{16, 17} which occurs slowly at room temperature and with increasing rapidity as the temperature is raised. At about 350°C. the effect begins to decrease, until at a sufficiently high temperature the effect can no longer be found. With increasing time these changes go through a maximum, beyond which the direction of the change is reversed. The time required for attainment of this maximum (or minimum) varies and becomes less as the temperature increases.¹⁸

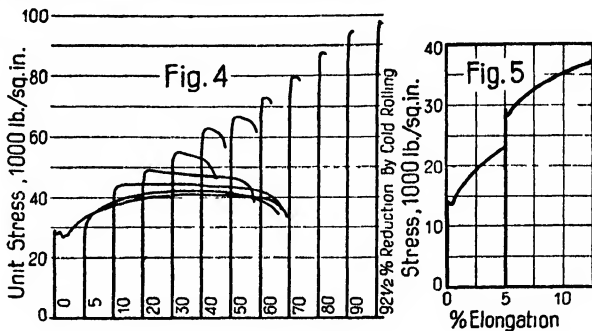


Fig. 4—Effect of cold rolling on the shape of the stress-strain curve of Armco Ingot Iron (Kenyon and Burns⁴).

Fig. 5—Effect on the yield point of aging electrolytic iron (Ludwik and Scheu¹³).

Plastic deformation of a sufficient amount eliminates the sharp yield point from the tension stress-strain curve when the test is made immediately, but this yield point is made to reappear by aging a long enough time at the particular temperature. This is shown for electrolytic iron in Fig. 5. Köckritz¹⁸ shows (in Fig. 6)

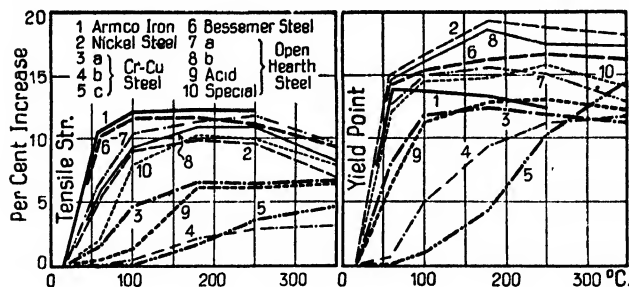


Fig. 6—Increase in yield point and tensile strength of various steels resulting from cold stretching 5% and heating for 1 hr. at the indicated temperature (Köckritz).

the increase in tensile strength and yield point of Armco Ingot Iron in comparison with other materials.

The aging capacity is not exhausted by small amounts of plastic deformation. The total effects may be built up by successive aging treatments, plastic deformation, and heating at temperatures¹⁹ below the blue brittle range (250–300°C.).

The behavior of iron plastically deformed at room temperature and aged at temperatures in the blue brittle range is duplicated in kind, though in somewhat different degree, by simple plastic deformation in the blue brittle range. Since at this temperature the rate of aging is very great, the resulting increase in strength values and decrease in ductility values manifest themselves during the tensile test on previously unstrained material. This has been shown by Jeffries and Archer¹⁹ and Kenyon²⁰ for Armco Ingot Iron. Fig. 7 is reproduced from the latter source. The temperature ranges for these maxima and minima change somewhat with testing speed; higher speeds tend to throw them to higher temperatures.

When plastically deformed iron is heated to various temperatures, the properties are altered. The amount of the change depends on the amount of cold deformation, the original condition (such as grain size) and the time and temperature of heating after cold working. These changes do not all take place at one temperature but are progressively greater as the temperature is raised, although there is a minimum temperature below which the changes are relatively small. The magnitude of these changes is increased if recrystallization occurs.²¹ According to Sato,²² the increased energy introduced during cold deformation is released at approximately 570°C. Tammann²³ shows a gradual decrease in electrical resistivity and thermoelectric force with increasing temperature of annealing, whereas the magnetic susceptibility remains unchanged up to about 750°C., at which temperature it suddenly increases.

Annealing of cold worked iron has a pronounced effect on the mechanical properties as determined at room temperature. Published data are almost exclusively for steels, the only results found for pure iron being those for Brinell hardness as reported by Tammann.²³ Under suitable conditions of grain size, amount of deformation, and annealing time and temperature, these changes in mechanical

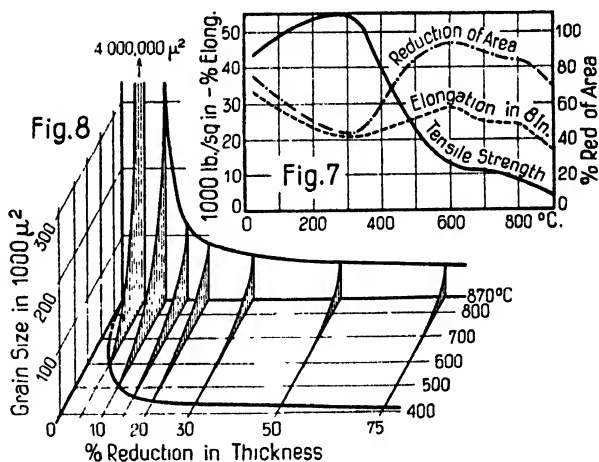


Fig. 7—Physical properties of Armco Ingot Iron at elevated temperatures (Kenyon²⁰).

Fig. 8—Recrystallization of iron.

Annealing of cold worked iron has a pronounced effect on the mechanical properties as determined at room temperature. Published data are almost exclusively for steels, the only results found for pure iron being those for Brinell hardness as reported by Tammann.²³ Under suitable conditions of grain size, amount of deformation, and annealing time and temperature, these changes in mechanical

properties are accompanied by a profound change in grain size. The metal undergoes *recrystallization*. It is possible, however, to soften cold worked iron without causing recrystallization.²⁰ The behavior of iron with respect to recrystallization is represented conveniently, though inadequately, by a three dimensional diagram relating to degree of cold work, temperature of heating, and resultant grain size. Fig. 8 is taken from Oberhoffer and Oertel²¹ and represents the general relationships, although it is believed that there is a critical temperature range that leads to the extreme grain growth, varying with the amount of deformation. The curve on the basal plane shows the amount of strain required to cause recrystallization at a given temperature and indicates that this may occur as low as 400°C. McAdam²² shows Armco Ingot Iron to recrystallize, under certain conditions, at 485°C. It is known that factors not represented in Fig. 7 affect recrystallization. Thus, the initial grain size is an important factor, small grains requiring less overstrain (as measured by changes in dimensions) to initiate recrystallization than large grains. Time of heating is also important, as well as rate of heating if this is slow. Type of deformation also affects the results, though it is probable that these may be shown to be equivalent upon the basis of a common unit for expressing the amount of deformation. It is also believed that the effective deformation of the individual grains is greater with small than with large grains for a given amount of total change in dimensions of the piece so that effect of grain size may be due principally to this difference in effective deformation.

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Wrought Iron

By A. W. F. Green*

Definition—Wrought iron is a ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron with which, without subsequent fusion, is incorporated a minutely and uniformly distributed quantity of slag.

Manufacturing Terms—A number of terms particularly applicable to wrought iron and the products manufactured from it are as follows:

Puddled Ball—The agglomerate cellular mass of refined iron intimately mixed with a siliceous slag, which is the result of hand puddling, mechanical puddling, or the pouring of molten refined iron into a siliceous slag as in the Aston or Byers' process.

Bloom—The product resulting from the squeezing of the "puddled ball".

Muck Bar—Bar rolled from a squeezed bloom.

Bushelling—The process of heating to a welding heat in a suitable furnace, miscellaneous iron, steel or a mixture of iron and steel scrap cut into small pieces. (The welded mass is then squeezed into a bloom and rolled into scrap bar for piling or fagoting.)

Fagoting—The making of a "fagot" or "box", the bottom and sides of which are formed of muck or scrap bars and the interior of miscellaneous iron scrap or a mixture of iron and steel scrap (Fig. 1).

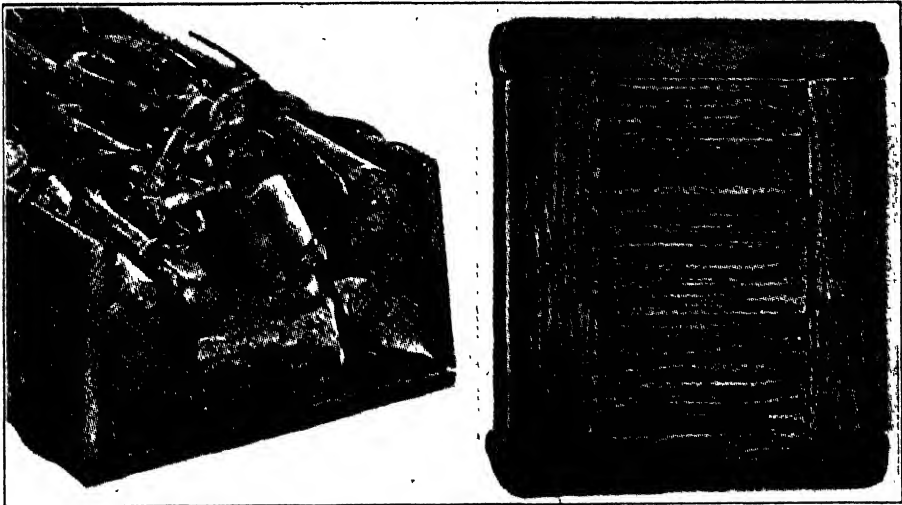


Fig. 1—Typical fagot for wrought iron (left). Fig. 2—Typical box pile (right).

Slab Pile—A pile built up wholly of flat bars of iron, all bars running the full length of the pile.

Box Pile—A pile of bars, the outside of which is formed of flat bars and the interior of a number of small bars, all running the full length of the pile. Used in the manufacturing of wrought iron bars (Fig. 2).

Refined Bar Iron or Refined Wrought Iron Bars—Iron bars rolled from a muck bar pile or from a box pile, of muck bars and wrought iron scrap free from steel, all bars running the full length of the pile (Fig. 3).

Double-Refined Iron—Iron to be classed as double refined shall be all new wrought iron, which shall be first rolled into muck bars. These bars shall then be

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twice piled and rolled. All iron shall be free from steel and from foreign scrap. The manufacturer may use his own mill products of at least equal quantity, but only in the first piling. In the final piling all bars shall be of the full length of the pile (Fig. 4).

Common Iron—Iron made from re-rolled scrap iron or a mixture of iron and steel scrap, no attempt being made to separate the iron and steel scrap (Fig. 5).

Methods of Manufacture—There are five methods employed for the making of wrought iron: 1. Hand puddling; 2. mechanical puddling; 3. the Aston or Byers, process; 4. bushelling; and 5. fagoting.

Hand Puddling Process—Wrought iron was in early times produced direct from the ore by reduction with carbonaceous fuel. In later times it has been produced by a variety of processes, usually however by indirect means. That is, the ore is first reduced to pig iron and the pig iron then transformed to wrought iron by the puddling or other process.

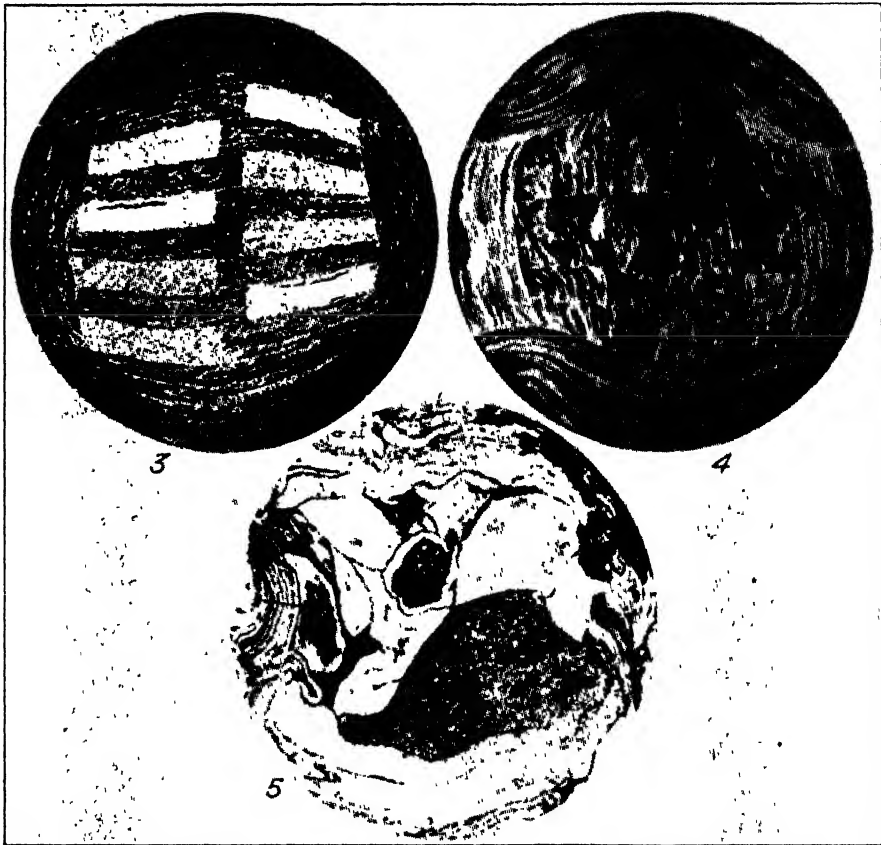


Fig. 3—Refined iron, macro etched. Fig. 4—Double refined iron, macro etched.
Fig. 5—Common iron, macro etched.

Henry Cort of England is credited with the inventions of the reverberatory type of furnace for the production of puddled wrought iron. The date given this invention is 1784. With only slight modification, the process has come down to the present day, and is commonly referred to as hand puddling.

The hearth of the hand puddling furnace is saucer shaped, and the lining is of sand. Iron oxide in the form of roll scale, iron ore, furnace cinder, or combinations thereof, is fettled into the sand bottom and sides of the hearth preparatory

to charging of the metal for puddling. The usual charges consist of pig iron. If a battery of furnaces is operated, it is often the practice to charge several different grades of pig iron, each furnace or portion of a battery of furnaces using a single type.

Heat is applied to the charge until it becomes molten. When molten, iron oxide in the form of roll scale, iron ore, furnace cinder, or combinations thereof, are added to the bath, which together with the siliceous oxide making up the bottom and sides of the hearth set up the refining action, tending toward the elimination of manganese, silicon, sulphur, phosphorus, and carbon. The first boiling period is called the low boil during which much of the manganese and silicon especially are eliminated from the metal. As the temperature of the bath rises due to the reaction, violent elimination of carbon begins and the period of the high boil takes place. During this time long blue carbon flames are expelled from the bath called the "Puddler's Candles". Necessarily, as the carbon is expelled, the melting point of the bath is raised and heat is actively generated in the furnace to maintain the bath molten and complete the reactions. The final stage is marked by the gradual freezing of the bath in the form of tiny iron particles called the *graining period*, at which time agitation is resorted to. The temperature of the furnace is no longer sufficient to keep the metal bath molten, although the siliceous slag having a much lower melting point, remains very liquid. The grained iron is gradually gathered into spongy balls and worked with the slag until sufficiently compact for removal to the squeezer. It is often necessary to drain excess slag from the furnace during this compacting operation, and on the other hand, siliceous slag forming ingredients must sometimes be added to further the welding and fluxing of the pasty iron particles.

The puddler determines the correct moment for removing the ball to the squeezer. The ball is a spongy mass of white hot iron dripping with slag. The squeezing and pressing operation further compacts the ball and ejects from it much of the excess slag it contains. The squeezed ball is then rolled into muck bars, billets, blooms, or other suitable shapes for reworking purposes.

Mechanical Puddling—The earliest efforts along the lines of mechanical puddling were to retain the furnace as it existed, and to substitute mechanical for manual power in manipulating the rabblers or stirring rods. The early developments which showed the most promise centered about the use of revolving furnaces. These were of three types: 1. Those having a variable axis of revolution; 2. those having an approximately vertical axis; and 3. those having a horizontal axis.

The Godfrey-Houson puddler was the best example of the first type. The Pernot furnace was probably the best example of the second type, and the Spencer, Menelaus, Danks, Crompton, and Ely inventions the best of the third type. The Ely furnace was used for puddling as late as 1934. Generally speaking, the horizontal type of revolving furnace succeeded in reducing the manual labor of puddling and balling and possessed the important feature of working on a hot bottom.

The mechanical and physical reactions encountered in mechanical puddling procedures are virtually the same as those in the hand puddling procedure. Some idea of what some of these inventions meant in increasing production of wrought iron may be gathered by these comparisons: The manual puddler produced balls weighing from 200-250 lb. each, and his entire output was approximately 2800 lb. per day. Each manually operated furnace had a fireman, a puddler's helper, and a puddler. The Ely rotary type of furnace which was oil fired, made balls averaging about 750 lb. each. One operator with two helpers managed two furnaces. Using molten iron from a cupola, these two furnaces produced 22,000-22,500 lb. of wrought iron in 8 hr. The Roe puddler on the other hand, can produce an 8000-10,000 ball or bloom using molten iron direct from the blast furnace every 60 min.

The Aston or Byers Process—The most startling invention having to do with the making of wrought iron is what is known as the Byers or Aston process. The work which resulted in this invention started about 1918 and constituted the most outstanding development in the manufacture of wrought iron since Cort's invention of the use of the reverberatory type of furnace early in the 18th century. The Byers or Aston process is of a far different nature than puddling either by hand or mechanical means. The melting of metal is done in cupolas. The molten

metal is then carried in suitable ladles where it is desulphurized and immediately thereafter, poured into Bessemer converters where it is refined according to regular steel procedure. Silicon, manganese, and carbon are oxidized in this refining operation. The blown metal is then tapped into a ladle and taken to the processing platform where it is poured into the ladle of the processing machine. The molten refined iron is poured at a predetermined rate into the ladle containing the molten slag. As the slag temperature is maintained several hundred degrees lower than the freezing point of the refined metal, the latter is continuously and rapidly solidified. This rapid solidification of the metal liberates its dissolved gases with sufficient force to shatter the metal into small fragments which settle to the bottom of the ladle. Due to the heating temperature and fluxing action of siliceous slag, these fragments weld together to form an agglomerate cellular mass in the form of a sponge. Immediately upon completion of the pour, the ladle is transferred and excess slag is poured off into an adjoining empty ladle. The sponge ball, weighing from 6,000-8,000 lb., is dumped at the rate of one, every five minutes on a platform of a 900-ton electrically driven press, where it is squeezed, collecting the mass into solid blooms for rolling.

Squeezing—There are three types of squeezers used for compressing the sponge balls into suitable shape for rolling into muck bar, bloom or billet sizes. The first is the small so-called coffee mill type, the drum operating on a vertical axis. The second, a generally larger type, except that the drum operates on a horizontal axis. The third, the steam, electric or hydraulic press types where pressures are applied on the ends as well as on the four sides of the ball.

Physical Properties

Sp.gr.	7.70
Melting point	2750°F.
Coefficient of thermal expansion—18-100°C.....	11.40 $\times 10^{-6}$
Heat conductivity—18°C.....	0.152
18°C.....	0.144
100°C.....	0.143

Chemical Analysis—Genuine wrought iron is identified because of its low carbon and manganese contents. Many specifications written to cover wrought iron analyses lay particular stress on the manganese content. It is generally conceded that freedom from contamination by steel or poor quality wrought iron can be shown if the manganese content is under 0.07%. Some typical chemical analyses are shown in Table I.

Table I
Typical Composition of Wrought Irons

Type of Iron	C	Mn	Si	P	S	Slag by Weight
Byers No. 1.....	0.08	0.015	0.158	0.062	0.010	1.20
Mechanical iron	0.08	0.029	0.183	0.115	0.015	2.85
Hand puddled iron . . .	0.06	0.045	0.101	0.068	0.009	1.97

Carbon—A carbon content over 0.10% is usually construed to mean imperfect refining, or awakens the suspicion that steel scrap has been used in making up the customary "piles".

Manganese—Well made wrought iron has a manganese content below 0.10%. If in excess of that amount imperfect refining may be indicated, or adulteration by use of steel in bushelling or piling.

Phosphorus—The phosphorus content of wrought iron is largely in the incorporated slag. Good wrought iron will contain from 0.08-0.160%, of which from 40-60% will be combined with the slag.

Sulphur—High grade wrought iron contains up to 0.035% sulphur. Higher amounts are known to produce "red shortness" and also indicate imperfect refining.

Silicon—The amount of silicon is usually from 0.10-0.20%. The proportion associated with the base metal is practically nil. Silicon under 0.10% indicates either that there is not the normal amount of slag, or that the composition of the slag is not normal for properly refined wrought iron. Silicon content about 0.20% may indicate poor slag distribution, probably due to improper mechanical working.

Slag—There is present in wrought iron a considerable amount of slag. A typical analysis of the slag found in wrought iron is as follows: SiO_2 , 14.58; Fe, 58.72; FeO , 70.49; MnO , 1.51; Al_2O_3 , 2.72; CaO , 2.59; P_2O_5 , 0.80; S, 0.08; Cu, trace; and Fe_2O_3 , 5.65. The amount of slag present in wrought iron by weight varies from 1 to as much as 4%, generally about 2.00%.

Alloy Wrought Iron—The most prominent of the alloy wrought irons are those containing nickel up to about 3½%. Molybdenum has been successfully alloyed and nickel and molybdenum together have been used. Copper is often found in wrought iron. It is possible to definitely alloy quantities of copper in the making of wrought iron. There is a question regarding its presence as to whether or not it has a deleterious effect on the red shortness characteristic. Numerous experiments have shown, however, that it does not materially affect this condition with percentages up to about 0.3% and it is entirely possible that its presence is desirous from the standpoint of corrosion. Nickel up to 3½% materially raises the elastic limit and tensile strength. Molybdenum does not seem to have any material effect on physical properties, and no concise data has been found to show that its presence has materially affected the general quality of wrought iron. An analysis of nickel wrought iron is as follows: C 0.06, Mn 0.035, P 0.070, Si 0.18, S 0.011, Ni 3.25, and slag 1.90.

Forging and Welding Ranges—The proper hot working or forging range is 2450-1650°F. However, the most reduction in forging should take place between 2450-2175°F.

The proper welding range is 2450-2300°F.

Tensile Properties at Low and High Temperature—The tensile properties of wrought iron without nickel are as follows: Tensile strength, psi., 42,000-52,000; yield point, psi., 26,000-35,000; elongation, per cent in 8 in., 25-40; and reduction of area, 40-55%.

When nickel is added to approximately 3.25-3.50% the values are about as follows: Tensile strength, psi., 55,000-60,000; yield point, psi., 45,000-50,000; elongation, per cent in 8 in., 25-30; and reduction of area, 35-45%.

Results of tensile tests at high temperatures are given in Fig. 6.

Bend Tests—Bend tests are resorted to in the testing of wrought iron to indicate not only the ductility but also quality, proper piling and freedom from adulteration with steel. These tests are made both hot and cold and also by nicking of cold bars.

Hot bend tests on highest quality wrought iron require bending the sample flat on itself from a temperature of 1700-1800°F. The poorer qualities of wrought iron are bent around a pin, equal in diameter to the diameter or the thickness of the bars being tested. It is sometimes required that hot bend tests be made at temperatures of 1400-1500°F. to determine whether or not the iron is "red short", a not uncommon condition.

Step Tests—The step test is applied to wrought iron to show that material is free from large slag inclusions as well as to determine methods of piling and contamination with steels. The bar as machined for the various steps is shown in Fig. 7.

Crush Tests—It is generally possible to tell the difference between galvanized wrought iron and galvanized steel by bending or flattening cold. If the zinc coating adheres firmly, the material is usually wrought iron. If the zinc starts to scale off at the beginning of the test the material is steel.

Pickling—The usual procedure for pickling of wrought iron pipe, rods, and bars, is to use a 4-5% solution of sulphuric acid at a temperature of 160-170°F. The pickling time for pipe varies from 1-1½ hr. and the rods or bars, 30-45 min.

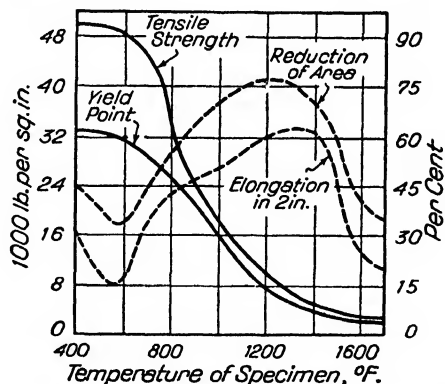


Fig. 6—Tensile tests of wrought iron at high temperature.

After pickling, material should be washed in water, and then passed through a bath of $\frac{1}{2}\%$ caustic soda and $\frac{1}{4}\%$ trisodium phosphate by volume.

Carburizing—Wrought iron can be case hardened. The usual process is to pack the parts in suitable compounds and quench in water from the box, or cool in the box and reheat to a suitable temperature and then quench in water.

The type of iron to be case carburized should be selected carefully since best results are obtained from iron made from box piles. The temperatures for carburizing and hardening are much the same as would be used for S.A.E. 1010 steel.

Protective Coatings—Protective coatings adhere firmly to wrought iron. This is to be expected because of the nature of the material. Fig. 8 shows the bonding

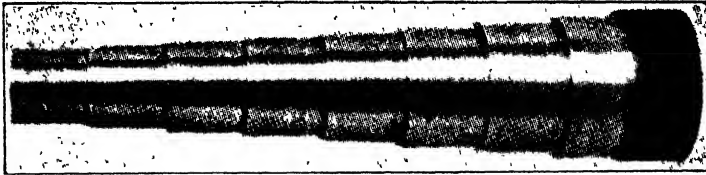


Fig. 7—Step test.

of a galvanized coating to wrought iron as compared with ordinary steel. In general, any protective coating that is applied to steel, except electropickling, can be applied to wrought iron.

Welding—The ease with which wrought iron can be welded is attributed to the relative purity of the base metal and the siliceous slag which confers on it a self-fluxing quality easily observable in hammer and pressure welds. The slag content of wrought iron makes it self-fluxing so uniform strong welds are rapidly secured.

Wrought iron lends itself readily to oxy-acetylene and arc welding. A fluxed or greasy surface is ordinarily an indication that the temperature

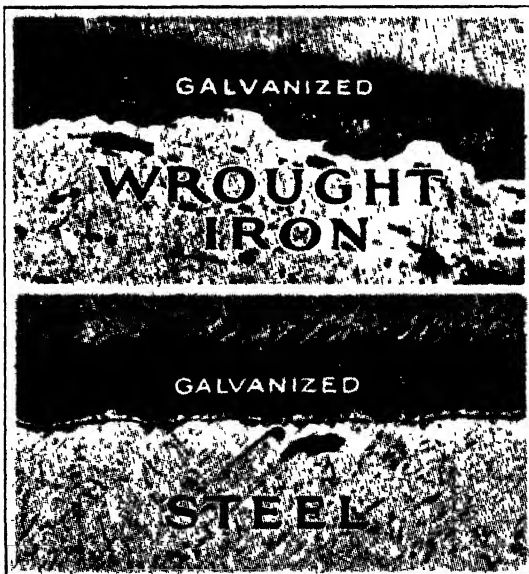


Fig. 8—Bonding of a galvanized coating to wrought iron and steel.

is sufficiently high to start applying fused secondary or weld rod metal. This is not quite true of wrought iron where a greasy appearance initially occurs due to the self-fluxing characteristic at a somewhat lower temperature. The temperature at which wrought iron fluxes is below the actual fusion point of the base metal and is too low for the application of the secondary metal. The welding should, therefore, be continued and the temperature of the edges where welding is to take place, raised somewhat higher. In this connection it should be remembered that wrought iron can stand higher heat without damage than other ferrous metals, and in general, should be worked hotter for best results.

Resistance to Corrosion—Wrought iron has demonstrated through centuries of application a remarkable resistance to progressive corrosion. The reason

for this is primarily the slag content and its distribution throughout the mass. Where wrought iron is exposed to corrective media, it is quickly coated with a film

of oxide or rust. As corrosion proceeds additional oxide is formed but the slag filaments begin to function as rust resisters. The initial oxide film is securely fastened to the surface of the metal by the pinning effect of the slag filaments thus serving to protect the metal from further oxidation.

It should not be taken to mean that all grades of wrought iron demonstrate the same properties of resistance to progressive corrosion. Bushed and fagoted iron, especially the types known as common iron, do not possess to any remarkable degree such property. Resistance to progressive corrosion is limited entirely to genuine wrought iron which has not suffered by adulteration through working.

Repeated Stress—From the point of view of laboratory tests alone, wrought iron is about the weakest ferrous material under repeated stress. The endurance limit of wrought ferrous metals determined in reversed or rotary bending is, in the absence of corrosion, about half of the tensile strength. Moore gives the following endurance limits in rotating beam and axial loading tests.

Materials	Endurance Limit, Rotating Beam, psi.	Axial, psi.	Tensile Strength, psi.	Charpy Notched Bar, ft.-lb.	Brinell Hardness No.
Wrought iron, longitudinal.....	23,000	16,000	46,900	17.5	105
Wrought iron, transverse.....	19,000	11,000	34,400	4.8	105
Ingot iron, as rolled.....	26,000	17,000	42,400	19.3	69
Structural steel, C 0.18% (as rolled)....	28,000	.....	61,500	....	...

Wrought iron is not materially handicapped in fatigue resistance by the presence of slag as long as the applied stress is longitudinal.

Izod Value for Wrought Iron

(Longitudinal Test. Average of 3 Tests)

Kind of Iron	Original Size	Izod Values, ft.-lb. "A" Notch at Right Angles to Flat Plane of Piling; "B" Notch at 90° to "A"	"A" "B"
Staybolt	1 in. rd.	45	44
Enginebolt	1 in. rd.	41½	42
A.S.T.M. 84-27C	1 in. rd.	44½	53
Bushed iron.....	1 in. rd.	51½	56
Bushed iron.....	1 in. sq.	51½	65
Bushed iron.....	2 x ½ in. flat	58½	58½
Common iron.....	1 in. rd.	63½	70
Common iron.....	1 in. sq.	62½	71
Common iron.....	2 x ½ in. flat	43	51

Applications and Forms Available—Wrought iron is used by the railroads, by shipbuilding industries, oil industries, for architectural use, by the public utilities, on farms, and for farm implements.

Wrought iron is available in blooms, billets, in all types of hammered bars and forms, and hot rolled shapes, including sheets and plates. Also, as wire for nails and barb wire manufacture and wire for general manufacture.

Weight of Wrought Iron—In calculating the weight of wrought iron bars and shapes, it is common practice to use the usual tables applicable to steel and deduct 2% from the weight shown in such tables.

Market Prices for Wrought Iron Products (May, 1936)

Cents Per Lb. Base

Some typical present-day prices for wrought iron are as follows:

Staybolt iron to meet A.S.T.M. Spec. A-84-33.....	6.25
Enginebolt iron to meet A.S.T.M. Spec. A-84-33.....	5.20
Single refined enginebolt iron (all new, no crop ends, all pieces full length of the pile).....	3.50
Single refined enginebolt iron (½ new puddled iron and ½ crop ends of equal quality).....	3.20
Refined wrought iron to meet A.S.T.M. Spec. A-41-30.....	2.30
Double refined wrought iron to meet A.S.T.M. Spec. A-41-30.....	4.24
Common iron to meet A.S.T.M. Spec. A-85-27.....	1.65

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Alloys of Iron and Nickel With Low Expansion Coefficients

By Dr. Matthew A. Hunter*

General Introduction—Alloys of iron and nickel possess many anomalous properties, depending on the relative proportions of the two constituents in the alloy. Guillaume discovered the alloys of low linear coefficient of expansion. In an intensive investigation of a series of various compositions, he found coefficients of linear expansion ranging from a small negative value (-0.5×10^{-6}) to a large positive value (20×10^{-6}). The alloy with 36% Ni with minor constituents of Mn, Si, and C, amounting to less than 1% had so low a coefficient of expansion that its length was practically invariable for ordinary changes in temperature. For this reason Guillaume gave the alloy the name "Invar."

Subsequently in the work of Guillaume and Chevenard, in cooperation with the Societe de Commentry-Fourchambault, an intensive study was made of the thermal and elastic properties of this class of alloys. Alloys with higher contents of Ni were found to possess higher coefficients of expansion. The alloy with 39% Ni had a coefficient of expansion corresponding to that of the low expansion glasses. The 46% alloy had a coefficient equivalent to that of platinum (9.0×10^{-6} per °C.) and received the name Platinite. A 42% nickel alloy when covered with copper to prevent gassing at the seal, is known as Dumet wire and is used to replace platinum as the "seal in" wire in incandescent lamps, and vacuum tubes. The 56% alloy

has a coefficient approaching that of ordinary steel (11×10^{-6} per °C.). Nilvar is identical with Invar (36% Ni).

In studying the elastic properties, Guillaume disclosed the alloy Elinvar, containing 36% of Ni and 12% Cr, which possesses an invariable modulus of elasticity over a considerable range in temperature as well as a low thermal expansivity.

Alloys containing less than 36% Ni have materially higher coefficients of expansion. The 18% Ni alloy has an expansion coefficient of 20×10^{-6} . These alloys belong in the irreversible class and by reason of their high coefficients are excluded from the present category.

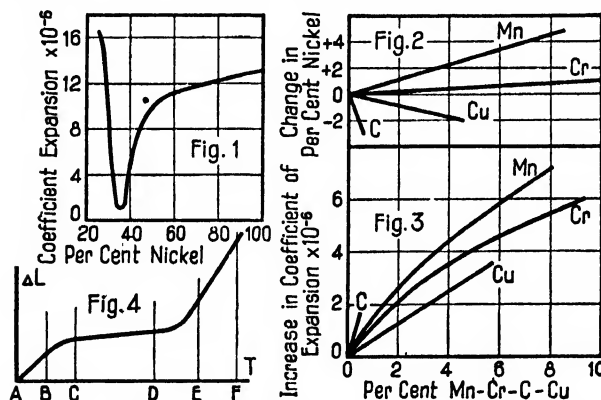


Fig. 1—Effect on the coefficient of linear expansion at 20°C. for nickel-iron alloys (0.4% Mn and 0.1% C) (Guillaume).

Fig. 2—Displacement of minimum expansivity by the additions of other metals (Guillaume).

Fig. 3—Change in minimum expansivity caused by additions of other metals (Guillaume).

Fig. 4—Change in length (ΔL) with temperature T of a typical Invar (Guillaume).

It has recently been found that certain percentages of cobalt can be used with advantage to replace Ni in the 36% alloy. An addition of 5% cobalt gives an alloy with an even lower coefficient than Invar and one less susceptible to variations in heat treatment.

Effect of Composition on Expansivity—The effect on the linear expansivity of variations in Ni content is given in Fig. 1.

The minimum expansivity occurs at about 36% Ni. A considerable influence is exerted on the position of this minimum expansivity by minor additions of other metals. The effect of additions of Mn, Cr, Cu, or C is shown in Fig. 2.

Minimum expansivity is shifted toward higher contents of Ni in the case of Mn and Cr and towards lower contents of Ni in the case of Cu and C. The minimum expansivity for any of these ternary alloys is, in general, greater than that of a

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typical Invar. The extent of the variation caused by these additions is given in Fig. 3.

Additions of silicon, tungsten or molybdenum produce effects similar to that of manganese and chromium—the minimum is shifted towards higher contents of Ni. Carbon is said to produce instability in Invar. Guillaume attributes this to the changing solubility in the austenitic matrix under heat treatment.

The replacement of some of the nickel by cobalt (up to 8%) produces a lowering in the expansivity of the alloy.

Physical Properties, Expansivity—It is not generally recognized that the low

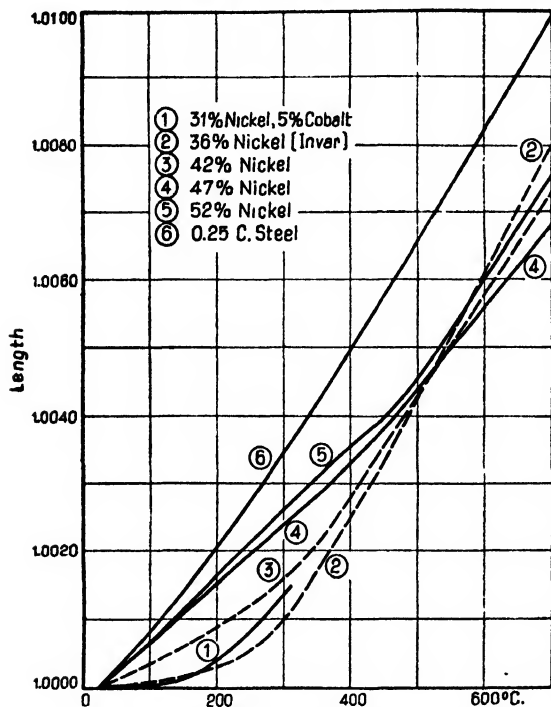


Fig. 5—Expansion of nickel-iron alloys (Hunter).

of the curve between C and D is then a measure of the coefficient of expansion over a limited range of temperature. The following figures are given by Guillaume for the coefficient of linear expansion between 0 and 38°C.

Expansion of Nickel Steels

% Ni	Mean Coefficient $\times 10^{-6}$	% Ni	Mean Coefficient $\times 10^{-6}$
31.4	3.395 + 0.00885 t	43.6	7.992 - 0.00273 t
34.6	1.373 + 0.00237 t	44.4	8.508 - 0.00251 t
35.6	0.877 + 0.00127 t	48.7	9.801 - 0.00067 t
37.3	3.457 - 0.00647 t	50.7	9.984 + 0.00243 t
39.4	5.387 - 0.00448 t	53.2	10.045 + 0.00031 t

Over wider ranges of temperatures the behavior of the alloys is represented by the curves given in Fig. 5. For purpose of comparison the expansion temperature curve for an ordinary steel is included.

Under the effect of heat treatment or cold work the values for the expansivity of Invar (or Nilvar) change considerably. The effect of heat treatment is shown in Table I by Russell.

The expansivity is greatest for well annealed material and least in the quenched samples.

Cold drawing also produces a lowering in the expansivity. The following coefficient figures are taken from the writer's own experience on two heats of Nilvar (Invar).

Effect of Quenching and Cold Drawing on Expansivity

Direct from the Hot Mill	Annealed and Quenched	Quenched and Cold Drawn Size 0.125-0.250 In.
1.4×10^{-6}	0.5×10^{-6}	0.14×10^{-6}
1.4×10^{-6}	0.8×10^{-6}	0.3×10^{-6}

Table I
Effect of Heat Treatment on Coefficient of Expansion

Treatment, °C.	Brinell Hardness	Mean Coefficient $\times 10^{-6}$	
After forging	142	17-100°C.	1.66
Quenched, 830	196	17-250°C.	3.11
Quenched 830, temp.....	250	18-100°C.	0.64
		18-250°C.	2.53
		15-100°C.	1.02
		15-250°C.	2.43
Heated to 830—19 hr., cooling to room temp.....	114	15-100°C.	2.01
		15-250°C.	2.89

It is possible by cold work following a quenching operation to produce material with a zero coefficient of expansion or even a negative one. In the latter case by careful annealing at a low temperature, the coefficient may be increased to zero again. These artificial methods of securing a low coefficient all tend to produce instability in the material. The low coefficients tend with the lapse of time and variations in temperature to recede to the normal values for the material. These "aging" tendencies are responsible for the secular and transitory changes which take place in the material. While these variations are of importance in special applications such as geodetic tapes, they are of little significance in ordinary operations. For such special applications it is essential to stabilize the material by submitting it to a slow cooling operation from 100-20°C. over a period of many months, followed by a prolonged aging at room temperature. But unless the material is to be subsequently used within the limits of the atmospheric variation in temperature, such stabilization is of no value.

Magnetic Properties—All nickel-iron alloys of the Invar class are magnetic at room temperature. They lose their magnetism at higher temperatures and become paramagnetic. The points of inflection in the curves in Fig. 5 are indications of the loss of magnetism. For a true Invar (36% Ni) Russell found that in a well annealed sample the loss of magnetism began at 162 and was completed at 271°C. In a quenched sample the loss began at 205 and was complete at 271°C.

Slow cooling through this range of temperature eliminates to a large degree the transitory and secular changes which are always troublesome in materials of this class.

Electrical Properties—The electrical resistivity of Invar ranges between 75 and 85 microhm cm. at ordinary temperatures. The temperature coefficient of electrical resistivity is of the order of 0.0012 per °C. over the low expansivity range. The thermoelectric power taken against copper is about 10 microvolts per degree.

Other Physical Properties—Sands has collected from various sources information on the miscellaneous properties of Invar from which the following are taken. The material was in the hot rolled or forged condition.

Melting point	1425°C. (2600°F.)
Density	8.0 g. per cc. (500 lb. per cu. ft.)
Tensile strength	65,000-85,000 psi.
Yield point	40,000-60,000 psi.
Elastic limit	20,000-30,000 psi.
Elongation	30-45%
Reduction in area.....	55-70%
Scleroscope hardness	19
Brinell hardness	160
Modulus of elasticity in tension.....	21,400,000 psi.
Thermoelectric coefficient	500×10^{-6} per °C.
Specific heat (25-100°C.)	0.123 cal. per g. per °C
Thermal conductivity (20-100°C.).....	0.0262 Cgs. units
Thermoelectric power (against copper), -96°C.....	9.8 microvolts per °C

The effect of temperature on the mechanical properties is shown in Fig. 6.

Processing—Considerable care has to be used in the hot working of these iron-nickel alloys, as they have a tendency to check and break up unless carefully handled. The annealing of Invar and related alloys should be done in a reducing atmosphere. These alloys are very susceptible to intercrystalline attack during annealing. The best results are, therefore, usually obtained by annealing in an atmosphere consisting of a large percentage of a neutral gas such as nitrogen and a small percentage of a reducing gas.

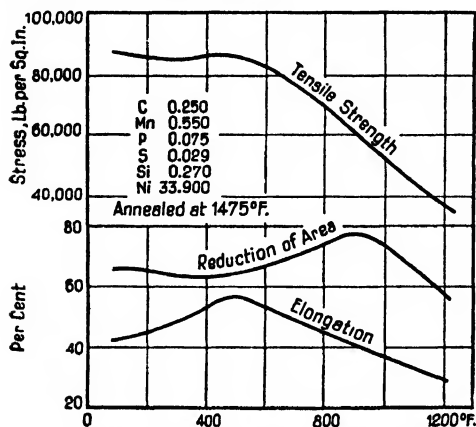


Fig. 6—Effect of temperature on the mechanical properties of forged 34% nickel-iron alloys (MacPherran).

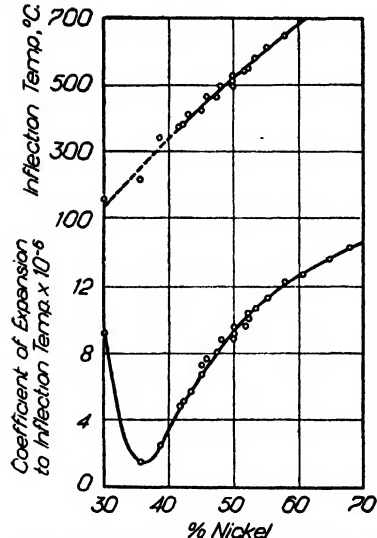


Fig. 7—Upper Curve—Effect of nickel on the inflection temperature of nickel-iron alloys.

Lower Curve—Effect of nickel on the average coefficient of expansion up to the inflection temperature of nickel-iron alloys.

containing 31% Ni and 4-6% Co produces a material with a zero coefficient of expansion in the hot rolled condition. Annealing and quenching appear to raise the coefficient somewhat, but in general the coefficient obtained from these alloys is lower than that obtained from Invar without subjecting it to cold work. An extensive investigation of this class of alloys has been made by Masumoto.¹

The cold rolling and drawing of these iron-nickel alloys is quite similar to that of nickel.

Heat Treatment of Invar—The annealing temperature of 750-850°C. (1380-1560°F.) gives good results. Quenching in water from these temperatures reduces the expansivity of the material, but induces instability both in actual length and in linear coefficient. To overcome these defects and stabilize the wire, a low temperature anneal (200-300°F.) followed by slow cooling to room temperature over a period of months is necessary. Slow cooling through the magnetic transformation has also been found satisfactory.

Applications

Absolute standards of length.

Rods and tapes for geodetic work.

Compensating pendulums and balance wheels in clocks and watches.

Expansion control in moving parts, automobile pistons.

Thermostatic strip.

Other Iron-Nickel Alloys—Alloys of iron and nickel, with nickel contents higher than Invar, retain to some degree the expansion characteristics of metals of the Invar composition.

Since further additions of nickel raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve rises with the increasing nickel content. While this increase in range is an advantage in some circumstances, it is obtained at a sacrifice of the low coefficient of expansion itself.

Scott² has published information on the coefficient of expansion of iron-nickel alloys up to the inflection temperature. Lohr and Hopkins³ give data on a more extended range of nickel contents up to 68% as given in Table II and Fig. 7.

Special Alloys—Certain ternary alloys with nickel and iron are interesting by reason of their special properties.

Super Nilvar—The replacement of some of the nickel by cobalt in an alloy of the Invar composition results in a lowering of the linear coefficient of expansion of the alloy. An alloy produces a material with a zero coefficient of expansion in the hot rolled condition. Annealing and quenching appear to raise the coefficient somewhat, but in general the coefficient obtained from these alloys is lower than that obtained from Invar without subjecting it to cold work. An extensive investigation of this class of alloys has been made by Masumoto.¹

Table II
Nickel-Iron Alloys
(Lohr & Hopkins)

Composition, %			Inflection* Temp. °C.	Average Coefficient of Expansion to Inflection, Temp. × 10 ⁻⁶
Mn	Si	Ni		
0.11	0.02	30.14	155	9.2
0.16	0.33	35.65	215	1.54
0.12	0.07	38.70	340	2.50
0.24	0.03	41.88	375	4.85
		42.31	380	5.07
		43.01	410	5.71
		45.16	425	7.25
0.35		45.22	425	6.75
0.24	0.11	46.00	465	7.61
		47.37	465	8.04
0.09	0.03	48.10	497	8.79
0.76	0.00	49.90	500	8.84
		50.00	515	9.18
0.25	0.20	50.05	527	9.46
0.01	0.18	51.70	545	9.61
0.03	0.16	52.10	550	10.28
0.35	0.04	52.25	550	10.09
0.05	0.03	53.40	580	10.63
0.12	0.07	55.20	590	11.36
0.25	0.05	57.81		12.24
0.22	0.07	60.60		12.78
0.18	0.04	64.87		13.62
0.00	0.05	67.98		14.37

*Note that in alloys with higher than 55% nickel, the inflection temperature is not in evidence.

Iron-Nickel-Cobalt Alloys—Scott³ has investigated the expansion properties of a series of low expansion iron-nickel-cobalt alloys over a range of cobalt additions up to 40%. Such additions raise the coefficient of expansion at room temperature. But since they also raise the inflection temperature, they produce an alloy with a moderately low coefficient of expansion over a wider range of temperature. Scott expresses his observations in the form of equations. If θ is inflection temperature, X the nickel content, Y the cobalt content, Z the manganese content and W the carbon content, the inflection temperature of any alloy in the group studied is given by:

$$\theta = 19.5 (X + Y) - 22 Z - 0 W - 465$$

Introducing the restriction that the nickel and iron content shall be so related as to depress the A_r point to about -100°C . then:

$$Y = 0.0795 \theta + 4.8Z + 19W - 18.1$$

$$X = 41.9 - 0.0282 \theta - 3.7Z - 19W$$

for inflection temperatures between 200 and 600°C .

The expansivities obtainable with these compositions are given by:

$$\alpha_1 \times 10^6 = 0.024 \theta + 0.38 Z - 1.2 W - 6.65$$

$$\alpha_2 \times 10^6 = 0.024 \theta + 0.38 Z - 1.2 W - 5.6$$

the former representing minimum expansivity and the latter mean expansivity when θ comes between 350°C . and 600°C .

Applications of these alloys in relation to seal in wires in glass are given by Scott⁴ and Hull and Burger. Scott's alloy "Kovar" and Hull's alloy "Fenico" contain approximately 54% iron, 28% nickel, and 18% cobalt.

Iron-Cobalt-Chromium Alloys—Masumoto² has made observations on an alloy containing 36.5-37% iron, cobalt 53-54.5%, and chromium 9-10% which has an exceedingly low coefficient of expansion, at times negative over the range $0-100^\circ\text{C}$. An alloy in this class is suggested by Hull as a seal in wire in special glasses—Fenichrome—37% iron, 30% nickel, 25% cobalt, and 8% chromium.

Elinvar—In determining the thermoelastic coefficients of nickel-iron alloys, Guillaume found that Invar had the highest elastic coefficient of all the alloys in the related group. There were, however, 2 alloys at 29% and 45% Ni which had zero coefficient, that is, their modulus of elasticity did not change with variations in temperature. But since, in these alloys, small variations in the nickel content produced large variations in the elastic coefficient, the commercial application of

the discovery was a difficult one. He found that the addition of 12% chromium to an alloy containing 36% nickel produced an alloy which had zero thermoelastic coefficient and one which was not susceptible to small variations in Ni content, which are to be expected in commercial melting. To this alloy he gave the name "Elinvar."

It has a particular application in the construction of such articles as hair springs and balance wheels in clocks and watches and in tuning forks used in radio synchronization, where an invariable modulus of elasticity is required. It has the further advantage in such situations of being nonmagnetic and comparatively rust-proof.

The composition of this material has been somewhat modified from the original specifications. Shubrooks gives the following limits for the material as now used.

Nickel	33-35%	Manganese	0.5-2%
Iron	61-63%	Silicon	0.5-2%
Chromium	4-5%	Carbon	0.5-2%
Tungsten	1-3%		

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Corrosion of Iron and Steel

By T. S. Fuller*

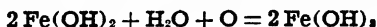
The problem of corrosion is of the greatest interest to all producers and users of iron and steel and it is most desirable that all should have as comprehensive an understanding of the subject as possible.

Corrosion Theories—Corrosion was first considered to be a case of simple oxidation, similar to that taking place when iron is heated in air. It was soon discovered, however, that not only was the presence of oxygen necessary, but also the presence of liquid water.

This discovery led to the acid theory of corrosion¹ which takes into account the necessary liquid water and oxygen, and postulates, in addition to these, the presence of an acid, usually carbonic. The acid is assumed to unite chemically with the iron, forming a soluble ferrous salt, which is later oxidized to ferric hydrate or rust, liberating the acid radical for further attack upon the iron. By this method it is quite evident that very minute quantities of acid will be sufficient to cause corrosion.

In 1903, Whitney² announced the results of experiments which led to the electrolytic theory of corrosion. Distilled water was boiled in test tubes to expel all the air and CO₂; polished samples of iron were added and the tubes sealed while the water was boiling. These tubes were allowed to stand in this manner for weeks without the slightest appearance of rust on the surface of the iron or appearance of a corrosion product on the glass or in the solution. At the end of several weeks the tubes were opened and a small amount of air admitted. A precipitate of ferric hydrate quickly settled out. Whitney's interpretation of the results follows:

Iron goes into solution in pure liquid water until the water becomes saturated with iron ions and a state of equilibrium is established. Until oxygen is admitted no precipitation of iron takes place. The conclusion is reached that iron goes into solution in liquid water in the absence of both an acid radical and oxygen and that corrosion is, therefore, essentially an electrolytic phenomenon. When the iron is dissolved by the water it first forms ferrous hydroxide, Fe(OH)₂, but due to its solubility it is not noticeable until a further reaction with oxygen takes place.



The ferric hydroxide, Fe(OH)₃, settles out of the solution as a reddish-brown precipitate and gradually passes to hydrous ferric oxide, Fe₂O₃, which is commonly known as rust.

These reactions will not take place in dry air or water free from oxygen, but as ordinary water always contains some dissolved oxygen corrosion will always take place when iron or steel is exposed to moist air.

The hydrogen peroxide theory³ postulates the presence of this substance as an intermediate product in the formation of rust and the biological theory⁴ regards the corrosion of iron as a phenomenon due primarily to micro-organisms.

The acid and electrolytic theories are of chief interest to students of corrosion. It is a difficult matter to say which of these two views is correct because of the difficulty of getting extremely pure substances to work with, but it is safe to say that 90% of the students of the corrosion of iron prefer to regard it as an electrochemical phenomenon.

Considerable impetus was given to the study of corrosion by experiments of Whitney, which led to the electrolytic theory. Later Cushman and Walker developed a reagent which became known as ferroxyl indicator, which demonstrates quite clearly the nature of ferrous corrosion.

The indicator has been described in detail by Cushman.⁵ Briefly, it may be prepared by mixing dilute water solutions of phenolphthalein and potassium ferricy-

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¹P. C. Calvert, *Experiments of the Oxidation of Iron*, Chem. News, 1871, v. 23, p. 98.

²W. R. Whitney, *Corrosion of Iron*, J. Amer. Chem. Soc., 1903, v. 25, p. 394.

³W. R. Dustan, H. A. D. Jowett, and E. Goulding, *Rusting of Iron*, Trans., Chem. Soc., 1906, v. 87, p. 1548.

⁴H. Richardson, *Rusting of Iron*, Nature, 1906, v. 74, p. 586.

⁵A. S. Cushman and H. A. Gardner, *Corrosion and Preservation of Iron and Steel*, 1910.

anide. If a more or less permanent record is desired, the solution is thickened with gelatin or agaragar. The action of the ferroxy indicator is this—a solution containing phenolphthalein becomes pink in the presence of an excess of hydroxyl ions; potassium ferricyanide in the presence of ferrous ions gives a dark blue precipitate. Therefore, with the indicator in contact with an iron surface, the positive areas—for example, points where iron is going into solution in the ferrous condition—are colored blue, and the negative areas, where there is a predominance of hydroxyl ions, are colored pink by these ions.

Corrosion Rate—The rate of corrosion of every piece of iron or steel depends upon the individual conditions existing in the particular locality in which the metal is in use, as well as upon the means which have been taken to prevent corrosion.

Bearing in mind that the two substances besides iron necessary for ferrous corrosion are liquid water and oxygen, corrosion phenomena are of many types. Iron samples, wholly immersed, corrode faster if the water is moving rapidly than they do if it is in a state of rest. The rate of corrosion of iron tanks or pipes holding water is much less if they are kept full than if they are alternately wet and dry. Atmospheric corrosion proceeds much more rapidly in districts where the atmosphere is chemically polluted by sulphur vapors and the like than it does in districts where the atmosphere is free from contamination. The corrosion of iron or steel is accelerated or retarded by contact with other metallic elements, depending on whether the elements are electro-positive or electro-negative with respect to iron. The corrosion rate increases with rising temperature.

The rate of corrosion is also dependent upon the character of the steel as determined by its chemical composition and heat treatment. Stainless steel with large amounts of chromium and the various alloys of nickel, chromium, silicon and iron are highly resistant to corrosion.

The chemical and structural compositions of iron and steel vary throughout the mass and because the various constituents have different electrical potentials, corrosion may be either accelerated or retarded thereby. The different electrical potential thus developed is usually comparatively great in badly segregated iron and steel or in metal containing impurities, all of which accelerate the corrosion.

Recent work of U. R. Evans emphasizes the influence of protective films upon the corrosion rate.

Stainless Steels—Because of their high corrosion resistance considerable quantities of alloy steels containing large amounts of chromium, and chromium and nickel have come into general use. The most common of these are the ones containing 14% of chromium, and 18% of chromium and 8% of nickel. The former alloy can be heat treated to give excellent physical properties varying over a wide range; the latter is austenitic in structure, and therefore cannot be heat treated to give specific properties, those properties being imparted only by the hot and cold working process. For maximum corrosion resistance it is necessary that both alloys shall have been heated and cooled in such a manner as to leave the carbides in solution.

Protective Coatings—Protective coatings for iron and steel form an important section of metal technology, and may be grouped under the following headings: 1. Paints; 2. metal coatings; 3. chemical coatings; and 4. greases.

Paints—Various specially prepared paints are used for protecting the surface of iron and steel. The paint must protect the surface from dampness, such as sea water, oxidizing gases, and smoke. Therefore no one paint is suitable for all purposes, and before a paint is applied the nature of the corrosive influence present must be determined.

Some paints protect the surface merely by the formation of an impervious film, such as asphaltum and tar. Other paints exert a chemical protective action, such as the ones containing linseed oil as the vehicle, and red lead as the pigment. The linseed oil absorbs oxygen from the atmosphere and by so doing forms a thick elastic covering. This reaction is hastened by boiling the linseed oil before using and adding salts of manganese or lead, which are called driers.

A few of the pigments used in paints are red lead, oxides of iron, lead sulphate, zinc sulphate, graphite, and hydrocarbons. The driers, vehicle, and pigments used must be inert to the steel; otherwise corrosion will be hastened instead of prevented.

Metal Coatings—The metal coatings include hot galvanizing, Lohmannizing, Sherardizing, hot tin dip, and electrolytic plates of tin, nickel, copper, and cadmium.

Galvanizing—Galvanizing is a process for coating metal with a thin layer of zinc. When the galvanized object is exposed to corrosive action, the zinc is dissolved in preference to the iron because it is more electro-positive.

The object to be galvanized is dipped in a bath of molten zinc (hot galvanizing) at a temperature about 810-840°F. In electro-galvanizing (cold galvanizing) the object to be coated with zinc is immersed in a bath containing a zinc salt as the electrolyte. The object to be coated is attached to the negative electrode and the metallic zinc constitutes the anode.

Lohmannizing—In this process, iron and steel sheets are first immersed in a bath containing an amalgamating salt and then pickled and dipped in two different baths of molten alloys. The finished surface is in a clean condition and is coated with the protecting metal. The metals used in this process are alloys of zinc, lead, and tin, the proportions of which are varied to suit requirements. Terne plate is an example of this process.

Sherardizing—In the Sherardizing process the articles are placed in a revolving drum or retort with zinc dust. A small amount of powdered charcoal is added to prevent oxidation of the zinc. The retort is closed and heated to about 700°F. This process is used principally for bolts and small castings.

Metal Spray Coatings—The process consists of passing metal wire through a specially constructed spray gun which melts and atomizes the metal to be used as coating. The surface to be sprayed must be roughened, usually by sand blasting, to afford good adhesion of the deposited metal.

Chemical Coatings—The chemical coatings include Parkerizing and Bower-Barff Finish.

Parkerizing—This process consists of immersing the objects to be treated in a solution of manganese dihydrogen phosphate; then heating to about the boiling point. The pieces are allowed to remain in the bath until effervescence ceases. They are then removed and dipped in oil. The surface produced has the appearance of gun metal.

Bower-Barff Finish—This process consists of heating the objects to be coated in a closed retort to a temperature of 1600°F. Superheated steam is then injected, forming a coating of both magnetic oxide (Fe_3O_4) and red oxide (Fe_2O_3) of iron. Then carbon monoxide (CO) is injected which reduces the Fe_2O_3 to Fe_3O_4 . These operations could be repeated alternately any number of times until a sufficient depth of oxide has been obtained.

Greases—Greases and oils of various grades are used to protect the surface of iron and steel by applying a thin film over the surface. This method is especially useful for parts of machines, tools, and steels which are to be put in storage or are to be shipped. For details of this method see the article "Slushing Compounds".

Deactivation—Of late much has been said and written about the deactivation of water. In general, the method consists of passing the water to be used in a closed system over scrap iron to remove the dissolved oxygen. Once the oxygen has been removed, theoretically the water may go on circulating indefinitely in the system without corrosive action. Such installations have proved to be very successful.

Dissolved gas can be removed from water by passing the water over an electrically heated heat-resisting ribbon, allowing the gas liberated thereby to escape.

Iron may be made immune to corrosion by making it cathode, that is, by making it the negative pole in a cell, with a potential just sufficient to balance the solution pressure of the metal. This method is not used extensively because it is costly.

Mechanical Deaeration—Speller⁷ in his book has given a very complete summary of the principles involved and methods used in mechanical deaeration, and has said in part:

"Dissolved gases can be removed from water, if the temperature and pressure conditions are so regulated that the gases become insoluble, and if a sufficient

⁷F. N. Speller, *Corrosion, Causes and Prevention* 2nd. Ed., 1935.

amount of time is allowed for their complete mechanical separation from the water. The greater the surface area of a certain volume of water, or the greater the size of the gas bubbles, the smaller is the time required to separate the gases. Physical agitation of the water tends to coalesce the fine bubbles into larger ones, which separate from the liquid in a very much shorter period of time. Most types of mechanical deaerators function by agitating water when it is exposed to favorable temperature and pressure conditions. Removal of dissolved gases may also be facilitated by sweeping or agitating the water with a large excess of some other gas which is less objectionable or is harmless. Thus, following the laws of partial pressure, the gases in solution are carried away or greatly diluted. This principle is illustrated by the common practice of spraying water, high in carbon dioxide, over a mass of coke or other inert material exposed to the air. In this way the water is intimately mixed with air, and although the carbon dioxide by itself is very soluble, the amount in solution is reduced under these conditions to as little as 5 parts per million. Following this principle, in hot-water heating apparatus, the vapors arising from the water should be swept away by a current of air free steam. Otherwise, the freed gases may be re-absorbed by the water, and complete elimination will be impossible."

Many different types and designs of mechanical deaerators are daily performing useful and valuable service.

Corrosion Tests—There are several tests made on iron and steel to determine their deterioration due to corrosion. The tests usually made are salt spray, total immersion, alternate immersion, accelerated electrolytic, subjecting to atmospheric conditions, and subjecting to gases.

The test specimens are of various designs and often the finished object is subject to the test. The deteriorating effect of the immersion tests is determined by the loss in weight as well as the appearance of the surface. The size of the specimen and the condition of the surface should be alike if possible in order to obtain a satisfactory comparison.

The solutions used may be natural water, such as sea water, city water, or mine water, or special solutions may be prepared containing salts and acid. When preparing special solutions it is advisable to use distilled water, otherwise the impurities will enhance corrosion.

The interpretation of results in all tests should be based on the relationship of the results to practical service conditions. There are many factors which make it difficult to obtain quantitative results and before drawing conclusions the following should be considered: The temperature of the solution, the machined surface of the specimen before testing, the length of time subjected to the test, apparatus used, and the care exercised in cleaning and drying the specimen before weighing.

Summary—There are many things which are as yet unexplained, but certain facts are so well established that they may be wisely borne in mind, as follows:

Liquid water and oxygen are necessary for the corrosion of iron.

The rusting of iron may best be regarded as an electrochemical phenomenon.

The rate of corrosion of every piece of iron or steel depends on its composition, upon the means taken for its protection, and upon the individual conditions existing in the particular locality in which it is in use.

Critical Temperatures for S.A.E. Steels

By M. J. R. Morris,¹ G. W. Gable¹ and Robert Sergeson²

Introduction—It must be remembered that the position of the critical points is altered and will vary over a wide range the faster the heating and particularly the faster the cooling. Also, the critical points will vary with every constituent in

Approximate Critical Temperatures

No.	On Slow Heating			On Slow Cooling			No.	On Slow Heating			On Slow Cooling		
	Ac ₁	Ac ₂	Ac ₃	Ar ₃	Ar ₂	Ar ₁		Ac ₁	Ac ₂	Ac ₃	Ar ₃	Ar ₂	Ar ₁
Carbon Steels							Nickel-Chromium Steels						
1010	1350	1405	1605	1570	1400	1255	3115	1355	1400	1500	1470	1380	1240
1015	1355	1410	1585	1545	1395	1265	3120	1350	1400	1480	1455	1380	1230
X1015							3125	1350	1395	1465	1400	1380	1220
1020	1355	1410	1570	1535	1395	1260	3130	1345	1380	1460	1360		1220
X1020							3135	1340		1445	1300		1220
1025	1355	1405	1545	1515	1405	1255	3140	1355		1415	1295		1220
X1025							X3140	1350		1430	1300		1240
1030	1350	1405	1495	1465	1405	1250	3145	1355		1395	1295		1220
1035	1345		1475	1455	1395		3150	1355		1380	1275		1215
1040	1340		1455	1415		1275	3215	1350	1410	1465	1415	1350	1240
X1040	1340		1450	1340		1270	3220	1350	1415	1480	1405	1355	1240
1045	1340		1450	1405		1275	3230	1340		1435	1395		1240
X1045	1335		1420	1330		1270	3240	1335		1425	1280		1240
1050	1340		1425	1390		1275	3245	1345		1400	1270		1225
X1050	1335		1400	1330		1270	3250	1340		1375	1255		1200
1055	1340		1425	1390		1275	3312	1330	1370	1435	1240		1160
X1055	1335		1400	1330		1270	3325	1335	1365	1400	1230		1160
1060	1340		1410	1370		1285	3330*	1320	1360	1380	1225		1145
1065	1340		1385	1345		1280	3335	1310		1360	1200		1100
X1065	1335		1380	1330		1280	3340	1290		1380	1180		1100
1070	1345		1370	1340		1280	3415	1330	1370	1425	1340	1300	1220
1075	1350		1365	1340			3435	1290		1380	1200		1150
1080			1360	1285			3450	1290		1360	1200		1100
1085							Molybdenum Steels						
1090			1360	1285			4130	1395	1435	1485	1405	1395	1280
1095			1360	1290			X4130	1395	1435	1480	1405		1250
10150*			1355	1290			4135	1395	1440	1475	1380	1360	1280
Free Cutting Steels							4140	1380		1460	1370		1280
1112	1355	1410	1590	1545	1395	1265	4150	1365		1395	1355		1280
X1112							4340	1350		1425	1220		725
1115							4345	1345		1415	1200		725
1120	1355	1405	1550	1510	1400	1255	4615	1335	1400	1485	1400	1320	1200
X1314							4620	1335		1470	1390		1175
X1315	1345	1420	1520	1495	1370	1245	4640	1320		1430	1300		1125
X1330	1320	1400	1490	1380	1360	1240	4650*	1315		1410	1260		1125
X1335	1315	1390	1420	1360	1340	1220	4815	1300		1440	1310		800
X1340	1310		1400	1340		1210	4820	1300		1440	1260		760
Manganese Steels							Chromium Steels						
T1330	1325		1480	1340		1160	5120†	1410	1460	1540	1470	1420	1295
T1335	1315		1460	1340		1165	5140	1370		1440	1345		1280
T1340	1315		1435	1310		1160	5150†	1330		1420	1280		1220
T1345	1315		1410	1300		1160	52100	1340		1415	1315		1260
T1350	1310		1400	1255		1105	Chromium-Vanadium Steels						
T1360*	1305		1405	1200		1095	6115	1420	1460	1550	1450	1380	1300
Nickel Steels							6120†	1410	1460	1545	1440	1380	1300
2015	1375	1475	1575	1450	1400	1215	6125†	1400	1440	1490	1390	1360	1295
2115	1345	1455	1525	1475	1380	1195	6130	1390	1440	1485	1370	1340	1285
2315	1300	1350	1440	1350	1260	1100	6135†	1390		1480	1370		1280
2320	1285	1345	1420	1235	1160	920	6140	1390		1455	1375		1295
2330	1275	1315	1400	1180		1050	6145	1390		1450	1375		1290
2335	1275		1375	1180		1050	6150	1385		1450	1375		1270
2340	1280		1360	1180		1060	6195	1370		1425	1360		1300
2345	1280		1350	1180		1060	Tungsten Steels						
2350	1280		1340	1180		1070	7260	1360		1430	1370		1310
2515	1250	1335	1420	1220	1140	825	Silicon-Manganese Steels						
2520*	1240	1340	1390	1175	1025	825	9255	1400		1500	1380		1320
							9260	1400		1500	1380		1215

*This is not a standard S.A.E. steel.

†The critical point determinations for these steels were obtained on a Leeds and Northrup transformation apparatus.

the steel. Therefore, the critical points given in the following tabulation may not always be consistent with the results obtained by others and should not be taken as absolute values for the critical points of the particular classes of steel listed.

The critical point determinations were made in a small laboratory electric furnace with automatic temperature control. The furnace samples were 1 in. round and $\frac{1}{2}$ in. thick and quenched in increments of 20°F. throughout the range on heating and cooling. The cooling rate was approximately the same as would be obtained in an uninterrupted furnace cooled annealing operation. Since the grain size and the exact rate of heating and cooling are not known, the results may be considered only as approximate.

Iron Alloys Containing From 3-20% Aluminum

By Dr. Kent R. Van Horn*

Aluminum is added to certain ferrous alloys in appreciable quantities to improve the electrical and magnetic properties or oxidation resistance of iron. The aluminum additions for these purposes range from 3-20% aluminum, and exceed the quantities used for nitriding steels or irons and for deoxidation. The commercial development of the alloys has occurred in recent years. The alloys may be classed according to two general types of applications, (1) electrical, and (2) heat resistance.

Electrical Iron Alloys Containing Aluminum—The improvement of the magnetic properties of iron or steel by aluminum is generally recognized. However, the beneficial influence of aluminum on magnetic permeability, like silicon, is indirect, namely, by its effect on carbon, oxygen and perhaps other elements, although directly aluminum would probably adversely affect pure iron. A 3½% annealed aluminum-iron alloy, vacuum melted, has a maximum permeability of 6 times, and a hysteresis loss of one-half of that of the commercial 3½% silicon transformer iron annealed in a similar condition.¹ The specific electrical resistance of iron is increased by 12 microns for each per cent of aluminum up to 3%. The electrical resistance of the 3½% aluminum composition is not so high as that of the 3-4½% silicon type. However, with the same method of preparation (vacuum melting) the silicon alloys are characterized by brittleness while the 3½% aluminum-iron has considerable ductility. There are some electrical installations where the aluminum-iron alloy has replaced the less expensive silicon types because the comparative brittleness of the latter was undesirable.

In 1934 patents were granted describing alloys containing aluminum for permanent magnets. An iron alloy containing 10-20% aluminum, 20% nickel, 5% cobalt, and no carbon, has qualities surpassing those of the 30% cobalt-tungsten permanent magnet type.² The exceptional properties of this material suggests an expanding field of magnetic applications.

Alloys Containing Aluminum for Electrical Resistors—A class of electrical resistors containing iron, chromium, and aluminum is marketed in this country as "Alcress" and "Ohmax",³ and as "Megapyr" in Germany. An alloy containing about 20% chromium, 5% aluminum, and the remainder iron, has a specific resistivity of 800 ohms per circular mil ft. If the aluminum content is increased to 10%, the material has a specific resistivity of 1000 ohms per circular mil ft. which is a higher value than that of the well known nickel-chromium resistors (650 ohms). The alloys containing aluminum also have an excellent resistance to oxidation at elevated temperatures. These two qualities and a lower density than the nickel-chromium type are utilized for applications where large resistance capacities are required for a minimum space, as in radio resistors. The alloys are more difficult to fabricate because of the presence of aluminum, but can be obtained for radio wires as small as 1 mil.

Another series of iron-chromium-aluminum resistors of similar composition and properties, but in addition contain some cobalt, is used in Europe and America for furnaces and electrical heating units demanding high temperatures or very compact units. This series of alloys called the "Kanthal" group consists of about 25% chromium, 5% aluminum, 3% cobalt, and the balance almost pure iron. The electrical resistance of the "Kanthal" series ranges from 812-872 ohms per circular mil ft. which is considerably higher than that of the 80% nickel, 20% chromium type (650 ohms). The density is lower than that of the nickel-chromium resistors, 7.15 as compared to 8.35 g. per cc. Ribbons or wires of the same sizes supplied in nickel-chromium can be fabricated and because of the superior resistance to oxidation are recommended for use at temperatures from 2000-2450°F. However, the tensile strength is low at elevated temperatures and it is necessary to provide suitable supports for elements in the installation.

A third iron base alloy⁴ of this type containing chromium, aluminum and small additions of other metals, for high temperature electrical resistors is known as "Smith Alloy No. 10". The chromium and aluminum contents are appreciably higher than in the two groups previously described, namely 37.5% chromium, 7.5% aluminum, and the balance iron. The alloy has the characteristics of the iron-

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chromium-aluminum type of high electrical resistance, excellent resistance to oxidation and can be hot formed into the required bends and helices. The electrical resistance is 1000 ohms per circular mil ft. and the density of the material is 6.9, so that the volume is 22% greater than the volume of the same weight of the nickel-chromium type. It is, of course, necessary to provide the correct type of refractories (nonsilica) and suitable supports which allow for the thermal expansion, growth and the sagging of the elements. The three iron-chromium-aluminum types are effective for high temperature applications such as forge furnaces, heat treatment of high speed steel, and burning of ceramic materials. These resistors also compete with the nonmetallic silicon carbide type in the higher part of the recommended temperature range.

Aluminum Heat Resisting Irons—The outstanding resistance of iron-aluminum alloys to the action of heat was reported in 1931 by Hauttmann.⁷ The oxidation resistance of the binary aluminum-iron alloys increases with aluminum content from 4-9% aluminum. Ziegler,⁸ in 1932, found that 4% aluminum when added to iron (vacuum melting) produced a forgeable alloy with good oxidation resistance properties. Alloys of 6% aluminum have a slightly inferior and 8% aluminum, superior resistance to heat compared to the 80% nickel, 20% chromium type. These aluminum-iron alloys appear to be forgeable and the presence of carbon has little effect on the resistance to scaling. The significance of these pertinent technical discoveries has been evidenced by the inception of a number of irons to which aluminum has been added to impart resistance to oxidation.

The American Iron and Steel Institute has formulated specifications of a standard heat resisting type, 406-D, containing 12-14% chromium, 4.5% aluminum, 0.12% carbon, balance iron. Castings and forgings are produced, to a limited extent, by several companies.

Alloys containing 7-15% chromium, 2-6% aluminum, and 1% carbon, are forgeable if the total aluminum and silicon content does not exceed about 5.5% with the silicon⁹ about 1%. The steels may exhibit complete oxidation resistance at 1550-1850°F. depending on the total quantity of aluminum, chromium, and silicon. These alloys are used commercially, but have no wide application because the beneficial properties can be procured more economically with silicon. However, in the future the cost of the aluminum steels may be reduced by improved melting practice.

Aluminum has been added to the 18% chromium, 8% nickel stainless steel in quantities up to 3%, to prevent high temperature scaling and increase machinability without impairing the properties.^{10, 11} Modified casting alloys of this type containing aluminum are used for heat resisting applications and have trade names of "Fahr-alloy" and "Hybnickel" with certain designating numbers.

High silicon, high aluminum cast irons are one of the four types of "refractory" cast irons widely used in Europe for heat resisting applications. These alloys containing 6-9% silicon, 3-7% aluminum have good refractory properties, high resistance to oxidation but are not employed where high tensile values are required. The silicon-aluminum cast irons are considerably cheaper than the other three common types of European "refractory" irons.

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High Yield Strength, Low Alloy Steels

By H. W. Gillett*

New types of low alloy steels have come on the market in the last few years to meet a demand for relatively cheap structural material with ductility and formability about the same as in ordinary structural steel, but with a decidedly higher yield point, and this without the necessity for heat treatment. To these requirements are added, for many purposes, those of weldability and resistance against atmospheric corrosion.

These steels are designed primarily for use where weight reductions are needed, especially in the transportation industries where lower dead weight without reduction in the strength of the members, opens the way to greater pay load. Cases where design is on the basis of static yield strength in tension can utilize smaller cross sections of high yield strength, but since the modulus of elasticity remains the same as in ordinary structural steel, stiffness has to be obtained by alterations in design to compensate for the smaller section and produce the necessary section modulus.

The necessary properties can readily be obtained from quenched and tempered carbon steels in small sections, but the large plates and shapes used in the structures for which these special steels are needed are unwieldy to heat treat and on account of the low depth hardening of carbon steels massive pieces would not be strengthened all the way through. Moreover, the strength obtained by heat treatment would be lost in the area affected by temperature, in welding, or flame cutting. It is therefore necessary that the required strength be obtained in the as-rolled condition.

Ordinary structural carbon steel of 0.20 carbon, 0.15 silicon, 0.50 manganese has a tensile strength of 50,000-65,000 psi. and a yield point of 25,000-30,000 psi. with an elongation in 8 in. of about 25-30%.

By raising the carbon to 0.40-0.45% the yield and tensile can be raised to 45,000 and 85,000 psi., the elongation dropping to 10-15%, while the notched impact resistance is at least halved. Decreased formability and the loss of ductility on cold working as in bending and flanging as well as air hardening and embrittlement in welding prevent the acceptance of such a steel.

By dropping the carbon and introducing alloying elements, the yield and tensile strengths may be increased without proportionately injuring ductility. Thus a steel of 0.15 carbon, 0.15 silicon, 0.30 manganese, 3.0 nickel may have a yield point of 40,000 and a tensile strength of 75,000 psi. with upwards of 20% elongation in 8 in. and up to about double the notched impact of ordinary low carbon structural steel.

Yield strength of this order was demanded in the early types of high yield strength steels, in cheaper ways than by the addition of 3% nickel. The carbon was cut to around 0.25-0.35% and the manganese increased to a higher figure, ranging from 0.75-1.75% with the lower manganese in the steels at the high end of the carbon range. The silicon was usually increased to around 0.30% hence these steels became known as "silicon structural steels," a misnomer since the increased strength was primarily due to the increase in manganese.

Less frequently the silicon was raised to 0.75-1.25% and the manganese held at 0.60-0.90%. The steels of 0.25-0.35% carbon with manganese and silicon as strengthening elements gave yield strengths of 45,000-65,000 psi. and tensile strengths of 80,000-95,000 psi. with elongations of about 16-22% in 8 in. In the lower carbon steels the notched impact resistance was held at about the level of ordinary structural steel.

These steels found use in bridges and similar structures, and in ship-building, and were acceptable for riveted structures. They are still used for such purposes, but are welded with some difficulty and their ductility is rather low for satisfactory cold forming.

Steels were then required with 50,000-60,000 psi. yield point with preferably not too high tensile strength, that is, a high yield ratio, and for a minimum of 22% elongation in 8 in., to insure satisfactory formability. Weldability was more insistently demanded, and since the thickness of plates was to be reduced in order to utilize the higher yield strength, improved resistance to atmospheric corrosion was called for so that the thinner plates would not pit through any quicker than the normal thickness of ordinary carbon steel.

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These requirements made necessary the adoption of lower carbon contents and the introduction of small amounts of alloying elements to make up for the reduction of the carbon, so manganese and silicon, chromium, copper, nickel, molybdenum and vanadium began to be utilized for their strength-giving effect.

Meanwhile the atmospheric exposure tests of the A.S.T.M. had shown that "copper-bearing steel," structural steel with around 0.20% copper, was improved in corrosion resistance. These tests showed also that increase in phosphorus content of a copper-bearing steel further improved the corrosion resistance. This fact pointed out by Storey¹ in 1921, was slow in being acted upon, but after about 10 years it was put to use. Beside the effect of phosphorus upon corrosion resistance, the facts that it is a strengthening element even more potent than carbon and that, if the sum of C + P is held below 0.25% the increase in strength can be had without static brittleness and with little effect upon impact, began to be realized. Hence phosphorus was added to the list of alloying elements.

While the bulk of the effect upon corrosion resistance is obtained at about 0.20% copper, further increase in copper to around 1½% confers some added resistance, and though the increase in strength due to 0.20% copper is almost imperceptible, addition of 0.40% or more, especially in conjunction with other alloying elements, was found to be worth while from the point of view of strength.

Moreover, when 0.60% copper or upwards is present, the steels become amenable to precipitation hardening, as Kinnear² showed, and as is discussed in the article on page 554.

Prior to the introduction of the higher percentages of copper for strength, all the older high yield point steels, of the carbon-manganese-silicon type, had become commercially available with the addition of around 0.20% copper for corrosion resistance. The addition of more than around 0.40% copper was held back by the fact that these higher copper steels are subject to preferential oxidation in scaling and tend to separate a film of copper beneath the scale if heated above the melting point of copper (see the article on page 558). This molten copper film penetrates in intergranular fashion and tends toward edge cracking and the production of checking on the surface in hot working. Lorig³ and others showed that the introduction of around half as much nickel as the copper present avoids cracking and checking, so that the use of a minor proportion of nickel in the higher copper steels became common. Strict control of soaking pit and reheating temperatures and rolling below the melting point of copper may also be utilized, and steel with 1% copper has been handled without nickel additions.⁴

Nickel is known to confer a degree of atmospheric corrosion resistance, somewhat analogous to copper, so the presence of even small amounts of nickel might be expected somewhat to enhance corrosion resistance, and the presence of say 2% should be definitely noticeable.

Chromium in large amounts, 12% and up, is of course known to confer superior corrosion resistance, while even 5% confers a definite improvement. The presence of 0.50-1% chromium does not have much apparent effect on corrosion and amounts of this order seem to be introduced chiefly as a strength-giving addition. Some improvement might be expected from such an amount. The proper balance of alloying elements cannot be predicted by a mere summation of the effects of the separate alloying elements. The steels of this class are not especially resistant to submerged corrosion, and their resistance to atmospheric corrosion depends on the exposure conditions being such as to build up a type of rust film that slows down further attack. They start to rust as rapidly as plain carbon steel.⁵

The grain refining effect of small amounts of molybdenum (0.20%) or vanadium (0.10%) is well known, and these, as well as aluminum or titanium (0.75%) are widely utilized to increase the ductility and notched impact resistance of as-rolled or normalized steels of the class under discussion. In some cases molybdenum is used in sufficient amount to act as one of the strengthening agents.

Several producers of ferroalloys or alloying elements have developed compositions embodying their products, and most of the major steel companies have selected a particular type composition selected from among the alloying elements mentioned above. The steels so devised are usually complex. One producer has followed the suggestion long ago made by Clamer⁶ and replaced part of the nickel in a low carbon 3% nickel steel, making the composition 2% nickel and 1% copper, without calling upon other alloying elements. Others utilize from 3-6 strength-giving elements beside carbon.

Most makers produce at least two grades, one (or more) in the range of 0.15-0.25% carbon plus moderate amounts of the chosen alloying elements, for nonwelding

uses, and a welding grade of 0.07 to (with some exceptions) 0.15% carbon. Several use 0.10-0.15% phosphorus, in which case the carbon is held from 0.07-0.13%, averaging around 0.10%. The low carbon grades are satisfactorily free from embrittlement on welding. A total of 0.25% C + P is probably a reasonable maximum, when the possibility of segregation of phosphorus in large ingots is considered.

With suitable precautions as to preheating before welding and stress relief annealing after welding, steels somewhat above 0.15% carbon are used for welding, but unless these precautions can be applied, the American Welding Society¹⁸ places 0.15% carbon as the upper limit for producing satisfactory toughness in the affected zone near the weld.* It suggests that the maximum tensile strength should be held down to 80,000-85,000 psi.

These welding grade steels, despite their low carbon content, 0.15% as a maximum, in usual commercial thicknesses of plate, as-rolled, fall within the ranges; yield point of 50,000-70,000 psi., tensile strengths of 70,000-80,000 psi. and 22-30% elongation in 8 in., with notched impact values at least equal to 0.20% carbon structural steel. The yield ratio of several of these steels is extraordinarily high. A minimum yield strength of 50,000 psi. is usually guaranteed and 55,000-60,000 psi. delivered. One maker favors the lower yield strength on the basis of formability and holds the average yield strength of its product as rolled, at 50,000 psi.

Several of the phosphorus-containing steels show endurance limits in rotary bending of 45,000-50,000 psi., the endurance limit approaching the yield strength. The endurance ratios obtained, 70-75%, are extraordinarily high. Endurance ratios on the higher carbon steels whose strength is gained from high manganese, run around the usual 45-50%, that is, approximately half the tensile strength. Endurance data are lacking on most of the newer steels, and the relative propensities toward notch propagation, which have a bearing on actual performance in service under repeated stress as contrasted with a laboratory test on a specimen free from stress-raisers, have yet to be evaluated.

Without citing properties for all grades of all these steels on the market the following may be summarized from the data supplied to Cone,⁶ and slightly modified on the basis of later information.

Tables I and II do not represent specification limits nor manufacturers limits of composition. The compositions are taken as representative ones, and the corresponding properties shown, where these are available. Some makers prefer to state minimum rather than average properties, so the tables should not be taken as placing each steel in its exact relation to the others.

That the plate thickness upon which the tabulated data were determined was not always stated is another reason why these figures should not be used for too fine intercomparisons. Further details can be had in the trade literature of the producing companies and in articles.⁶⁻¹⁴

The data do show the improved ductility of the low carbon group compared with the high carbon group, also that in the former class the desired yield strength may be attained with a wide variety of alloying elements. Other combinations than those listed could be employed, and there is no finality or standardization as to composition in sight.

Foreign steels of this type have also been developed. A copper-chromium steel commercially produced in England was stated in 1934 to contain 0.22-0.26 carbon with about 0.10 silicon, 0.80 manganese, 0.30 copper and 0.90% chromium. More recently Britton¹⁶ indicated that both the carbon and chromium had been dropped, citing a composition of 0.15 carbon, 0.07 silicon, 0.65 manganese, 0.31 copper, 0.65% chromium, which in sheet 0.035 in. thick showed 67,000 psi. tensile, 49,500 psi. yield point, 13% elongation in 8 in. In discussion of Britton's article, Portevin gave the following analyses for French steel of this type:

C	Si	Mn	Cu	Cr
0.15	0.17	0.70	0.57	0.48
0.08	0.94	0.32	0.42	0.80

According to Zeyen¹⁷ the German railway specifications for "Stahl 52," call for limiting the composition to the following maxima 0.20 carbon, 0.50 silicon, 1.20 manganese, 0.55 copper, 0.06 phosphorus, 0.06 sulphur (P + S 0.10), to which may be added either 0.30 manganese (making the Mn 1.50), or 0.40 chromium or 0.20 molybdenum.

*Not all producers agree with this, feeling that, if the rest of the composition is suitable, 0.18 or perhaps even 0.20% may be permitted.

Table I—Low Alloy Steels for Welding Without Preheating or Stress Relieving Annealing
Longitudinal specimens as-rolled $\frac{1}{2}$ to $\frac{1}{4}$ in. plate or 1 in. rod unless noted.

No.	Approximate Composition, %										Yield Point, psi.	Tensile Strength, psi.	Elong., % 8 in.	Red. Area, %	Impact, ft. lb.		Endurance Limit, psi.
	C	Si	Mn	P	Cu	Cr	Ni	Mo	V	Charpy					Izod		
1	0.13	0.15	0.90	....	0.20 ^a	....	....	0.50 ^b	....	50,000	80,000	23	55	..	..	.....
2	0.16	0.20	1.20	....	0.20 ^a	....	....	....	0.10 ^a	60,000	80,000	21-28	60-70	..	60-110	.....
3	0.14	0.70	1.10	....	0.20 ^a	0.50	....	....	....	50,000	75,000	25	40	50	..	.....
4	0.08	0.05	0.38	0.11	0.65	....	0.75	0.10	....	50,000	70,000	27	60	..	130	49,000 ^c
5	0.09	0.40	0.70	0.10	0.60	0.25	0.33	....	....	50,000	75,000	25	..	..	75	49,000 ^c
6	0.10	0.50 max.	0.75	....	0.50	0.25 max.	0.25 max.	....	....	50,000	70,000	25	..	..	..	.....
7	0.10	0.30 max.	0.60	0.10	1.10	....	0.55	....	....	50,000	75,000	25	60	55	..	49,000
8	0.09	....	0.70	0.20	1.40	....	0.80	0.10	....	55,000	70,000	25	50	25	..	45,000
9	0.10	0.75	0.20	0.13	0.40	0.90	....	....	....	50,000	70,000	25 (in 2 in.)	..	40	60	45,000
10	0.08	0.30 max.	0.55	....	1.00	....	2.00	....	....	55,000	75,000	25	60	40	..	40,000

^aCopper content when copper is desired.
^bFor heavy sections, 0.25% Mo for light sections.
^cManufacturers allow up to 0.15% C max. Safe weldability is claimed due to effect of V.
^dOn sheet.

^aCopper content when copper is desired.

^bFor heavy sections, 0.25% Mo for light sections.

^cOn sheet.

Manufacturers allow up to 0.13% C max. Safe weldability is claimed due to effect of V.

Table II—Low Alloy Steels for Riveted Structures

Some can be welded by preheating and stress relief annealing. Longitudinal specimens as rolled, $\frac{1}{2}$ - $\frac{1}{4}$ in. plate.

No.	Approximate Composition, %										Yield Point, psi.	Tensile Strength, psi.	Elong. % 2 in.	Red. Area, %	Impact, ft.-lb. Izod.	
	C	Si	Mn	P	Cu	Cr	Ni	Mo	V							
1	{0.28 0.35 0.30 max.	0.25 0.15 0.50 max.	1.50 1.40 0.90 max.	.... .... .... ....	0.50 0.20 0.50 ....	.... .... 0.25 max.	.... .... 0.25 max.	.... .... .... ....	.... .... .... ....	.... .... .... ....	55-60,000 60-70,000 65-90,000 55,000	80-90,000 75-90,000 90-95,000 85,000	20-35 20 20-30 20	.... .... 60-70 ....	.... .... .... ....	40-60
2	0.20	0.20	1.45	0.09	0.20*	....	....	0.12	....	65-90,000	90-95,000	20-30	60-70	....	....	....
3	0.17	0.75	1.00	0.09	1.00	0.50	....	0.20	....	55,000	85,000	20-28	50-65	....	....	....
4	0.20	0.75	1.25	....	0.20*	0.50	....	....	....	55,000	85,000	20-28	50-65	....	....	....
5	0.25	....	1.00	....	1.40	....	0.90	0.25	....	70,000	90,000	15	....	....	....	....
6	0.25	....	1.00	....	0.95	....	1.90	....	....	65,000	90,000	25	55	....	....	....
7	0.22	....	0.80	....	....	....	....	....	....	....	....	....	....	....	....	....
8	0.13 ^b	....	0.55	0.09	0.40	....	....	....	....	58,000	70,000	23	59	in. plate	....	....
9	0.28 ^b	0.15	1.40	....	0.25	0.12	....	....	....	85,000	105,000	12	....	....	....	....

^aWhen specified.

Steels 8 and 9 are given their strength by low finishing temperature, below the critical. The other steels could be made stronger and less ductile by similar procedure. Steel 8, of weldable composition is not listed in Table I since strength conferred by cold work will not be expected to be retained in applications heated in welding. Steel 8 has not been included in Table I for this reason though the makers state that the strength of welds is practically that of the plate. Hot forming up to 1500° F. is said not to affect the properties. The endurance limit of No. 8 is given as 45,000 psi.

^aWhen specified.

Steels 8 and 9 are given their strength by low finishing temperature, below the critical. The other steels could be made stronger and less ductile by similar procedure. Steel 8, of weldable composition is not listed in Table I since strength conferred by cold work will not be expected to be retained in locations heated in welding. Steel 8 has not been included in Table I for this reason though the makers state that the strength of welds is practically that of the plate. Hot forming up to 1500°F. is said not to affect the properties. The endurance limit of No. 8 is given as 45,000 psi.

Zeyen gives the following for plate 0.47 in. thick, as representative of German practice:

	C	Si	Mn	P	S	Cu	Cr	Mo	Tensile Strength, psi.	Yield Point, psi.	Elong., %	Impact, mkg./cm. ²
Krupp	0.18	0.50	1.43	0.026	0.017	0.48	...	...	86,000	55,500	25	10.5
Union	0.17	0.45	0.87	0.037	0.017	0.49	0.17	...	74,000	50,000	20	12.5
Gutehoffnungshütte	0.15	0.52	0.98	0.031	0.024	0.25	0.02	0.11	74,000	47,000	21	13

From the known costs of the alloying elements used it is obvious that some of the compositions listed are more expensive than others. But ability to be rolled into difficult shapes, uniformity of properties in sections of varying sizes and other manufacturing matters affect the cost of the finished steel.

From the users' point of view the weldability and the properties of the welds, the ability to be cold formed, and the actual corrosion resistance in service are features upon which the final choice will depend. Without doubt the steels differ somewhat in these properties, but evidence for full evaluation will take years to accumulate.

Sufficient evidence as to usefulness is at hand so that the steels are coming into use, especially in the construction of light weight freight cars. Streetcars, trucks and busses utilize them to some extent. Their use in shipbuilding is beginning.^{11, 12}

Gibson¹³ has described their use in heavy welded construction, such as turbine runners, engine bases in submarine service, and especially in such things as drag line buckets. When large sections are available uses of this type will increase.

They seem to have little application to automobile or aircraft needs which are met by heat treated steels, but when the problem of increasing payload comes up in construction so heavy that quenching and tempering are not applicable, the low alloy steels deserve consideration.

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Properties of Forgings in Heavy Sections

By A. W. Demmler* and Jerome Strauss†

As a prerequisite to the heat treatment of steel to meet definite physical properties, sound steel must first exist in the forging; this, of course calls for an initially sound ingot. While both acid and basic open hearths are applicable, the largest forging ingots ordinarily are of acid steel poured into corrugated big-end-up molds. Acid practice necessitates raw materials low in sulphur and phosphorus. A sound ingot is only possible with fully killed steel and to insure thorough deoxidation, the final deoxidation is commonly accomplished in the ladle when large ingots are involved. The nature of this deoxidation or final control practice is of special concern especially when transverse properties are paramount for the application. Here a minimum of banding is desirable aside from any regulation of grain size.

Large ingots may stand (in the mold) for days to insure complete solidification before being transferred to the forge furnace, and further, a large hot top is necessary to supply the shrinkage in the body of the ingot as the metal freezes. Large ingots should be transferred to a heating or equalizing furnace while there is still color in the body; this is vital to avoid severe stresses in a coarsely crystalline mass which would otherwise have a distinct temperature gradient from surface to center that might involve transformation changes, plastic deformation in certain zones and internal ruptures. Large masses in the as-cast state do not possess ductility to a marked degree. It is advisable first to allow the ingot to equalize from center to surface with the furnace in the range of 1200-1500°F. before attempting to raise the temperature. The heating to forging temperatures (approximately 2200°F.) should not be rapid as a serious temperature gradient is undesirable. Where appreciable alloy content is present the rate of heating should be somewhat slower than one hour per inch of thickness. Nonuniform heating or impingement of the heating flame may also result in serious damage to the ingot. No forging work should be attempted until the heat has thoroughly soaked into the heart of the section.

The initial working should consist of slight reductions on all sides to consolidate the metal. After the steel has received this light working, greater reductions can be safely made. For penetration of the working to the center of large masses a press is necessary. With full penetration during the forging operation it may be possible to weld clean ruptures which may have originated in the solidification of the ingot or in its initial heating. Full penetration of the hot working is also necessary to break down the coarse crystallization of the steel throughout the heavy section. The finishing temperature in forging should be low enough to avoid excessive grain growth in the steel after it is laid down; at the same time it must not be so low as to result in forging ruptures in those alloy steels that have high strength at elevated temperatures. Common practice is at least 3:1 reduction in cross section from the ingot while 2:1 reduction is not uncommon where transverse tests are specified; of course, upsetting (which may be in several stages) or expanding is beneficial to transverse properties also.

Caution is advisable in cooling the finished forging and also any balance of the ingot or bloom which may remain. Simple low carbon steels may usually be cooled in still air, but higher carbon or alloy steels should be immediately annealed or cooled in ashes; otherwise, internal ruptures may develop. Annealing may be absolutely necessary to permit ready machining of some compositions. Reference is suggested to Handbook articles for Large Forgings and the Heating, Forging, Annealing, and Normalizing of Locomotive Forgings.

Where design permits, it is best to bore heavy forgings. The boring is beneficial from practically all viewpoints: Unsound metal may be removed, segregation may be eliminated, inspection is simplified, and heat treatment is simplified and rendered more effective.

The more common heat treatments for large forgings are either annealing or normalizing or possibly both; a tempering treatment 1050-1250°F. is advisable following normalizing while the cooling from this lower temperature may be in the furnace or in still air. Although the greatest ultimate grain refinement will result from a treatment temperature not greatly above the critical, an initial higher temperature normalizing or annealing is generally necessary to develop homogeneity of structure. In a large forging, especially if finished hot on the press, a single homogenizing and

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a single refining treatment will probably not accomplish satisfactory refinement; several stages of refining are usually necessary.

Where conditions will permit, liquid quenching, spray quenching, or cooling in an air blast will result in higher strength properties; of course, a tempering treatment is necessary. Reasonable uniformity of section throughout the forging is vital for this more drastic quenching, and sharp fillets must be avoided.

A number of different steel compositions have been used for heavy forgings and the properties obtainable for different types of heat treatment are presented in the following tables. The air quench treatments are single treatments while for the most part, the liquid quenched forgings have been initially normalized. These forgings are applied to such parts as crusher shafts, rams, rotor shafts, ship propeller shafts, rolling mill shafts, sugar mill shafts, or axles.

Melting and forging details have been available in only a few cases, so that none of these features has been included. However, the nature of the refining, final deoxidation and grain size regulation enter into the ultimate properties, more particularly as mentioned earlier, when transverse properties are involved.

Composition and Tension Properties of Large Forgings Normalized and Tempered
(All solid sections, midway longitudinal tests)

Forg- ing Dia., in.	Composition, %						Mechanical Properties			
	C	Mn	Cr	Ni	Mo	V	Yield Point, psi	Tensile Strength, psi	Elong., % in 2 in.	Red. of Area, %
13	0.21	0.80			0.46		46,900	74,300	28	57
14	0.41	0.64				0.10	45,200	77,300	31	62
12	0.49	0.88				0.19	63,500	101,300	26	52
6	0.39	1.08			0.15		63,100	104,000	26	54
13	0.26	1.62				0.18	75,000	96,400	26.5	58
9	0.29	1.71				0.19	81,400	104,500	26	61
6	0.24	1.53			0.21	0.17	77,200	97,000	25.5	67
11½	0.41	0.64	0.90		0.20		80,000	103,000	19.5	38
9	0.41	0.71	1.29		0.20		61,600	99,300	25	50
10	0.48	0.73	0.91		0.18		63,900	105,800	24	51
6	0.39	0.60	1.40		0.35	0.21	118,000	147,100	16.5	50
12	0.23	0.89		2.62			60,100	86,000	30	68
12	0.34	0.67		3.11			61,000	93,000	27	62
12	0.32	0.62	0.61	1.47			60,100	99,700	27	62
12	0.44	0.69	0.69	1.40			77,000	102,000	22	61
13	0.31	0.82		1.81	0.34		79,200	99,200	22	60
6x6	0.38	0.64		1.84	0.25		74,000	102,000	25	58
10	0.28	0.70		2.92	0.35	0.15	81,500	107,000	24	60
9	0.34	0.65		2.87	0.34	0.12	94,000	115,000	22.5	56
12	0.26	0.63	0.53	2.17	0.25		78,000	95,300	26.5	70
11	0.29	0.68	0.90	2.66	0.31		89,000	111,500	19	51
12	0.39	0.67	0.83	1.33	0.24		68,000	98,500	21.5	51
10	0.33	0.49	0.81	2.30	0.42	0.18	81,000	107,000	23	58

Composition and Tension Properties of Large Forgings Quenched and Tempered
(All solid sections, midway longitudinal tests)

Forg- ing dia., in.	Composition, %						Mechanical Properties			
	C	Mn	Cr	Ni	Mo	V	Yield Point, psi	Tensile Strength, psi	Elong., % in 2 in.	Red. of Area, %
10	0.51	0.81				0.18	80,700	111,000	23.5	48
13	0.23	1.68				0.19	86,000	108,000	25	64
6	0.24	1.53			0.21	0.17	80,200	105,300	20.5	61
11	0.42	0.74	0.97		0.20		108,000	123,300	15	38
6	0.51	0.65	0.87		0.20		101,200	132,500	17.5	51
6	0.51	0.65	0.87		0.20		81,400	116,600	24	61
13	0.44	0.68	0.88			0.16	88,200	124,000	22.5	57
8	0.51	0.67	0.88			0.17	91,700	121,000	22	56
9½	0.38	0.70	0.97		0.30	0.09	116,500	141,000	18.5	54
6	0.39	0.60	1.40		0.35	0.21	138,400	165,200	16.5	57
9	0.23	0.93		2.60			75,500	95,000	28	61
12	0.27	0.86		2.73			84,900	105,300	23	63
11	0.37	0.58		3.50			82,000	101,000	23	57
9	0.37	0.63	1.24	3.00			110,000	127,000	20	56
8	0.38	0.65	0.71	1.20			87,000	109,000	21.5	54
12	0.49	0.55	1.10	1.75			104,000	118,000	18	57
13	0.31	0.32		1.81	0.34		83,400	100,400	22.5	60
9	0.32	0.70	0.62	2.35	0.31		116,000	139,000	20.5	54
8	0.37	0.78	0.72	1.79	0.41		117,000	138,000	21.5	59
8	0.38	0.69	0.62	2.12	0.31		134,500	151,000	18.5	56
9	0.31	0.66	0.77	1.84	0.43	0.16	116,500*	143,700	18	59
11	0.33	0.83	0.74	1.85	0.41	0.11	94,000*	117,000	20	52

*Elastic limit.

Coefficients of Linear Expansion of S.A.E. Steels

By Peter Hildner*

Chemical Composition^a, %

S.A.E. No. ^b	C	Mn	Si	P	S	Ni	Cr	Misc.	Treatment
Carbon Steels									
1010*	0.07	(0.08)	0.01	0.01	0.02	....	....	Cu 0.02	Annealed
1015	0.14	0.39	0.31	0.015	0.030	....	....	Cu 0.10	Not known
1015	0.17	0.42	....	0.012	0.035	....	....	....	Roller
1015*	0.18	0.34	0.10	(0.051)	0.044	....	....	Cu 0.10	Not known
1020*	0.22	(0.12)	0.01	0.01	0.03	....	....	Cu 0.04	Annealed
X1020	0.19-0.25	0.07-0.02	0.24-0.28	0.019-0.023	0.015-0.022	....	....	....	Cast
1030	0.31	0.65	0.23	0.013	0.028	....	....	Cu 0.13	Not known
1035*	0.33	(0.12)	0.03	0.01	0.03	....	....	Cu 0.03	Annealed
1040	0.42	0.68	0.23	0.012	0.025	....	....	....	Annealed
1040*	0.40	(0.11)	0.07	0.01	0.03	....	....	Cu 0.03	Annealed
X1040*	0.41	0.64	0.09	(0.052)	(0.061)	....	....	....	Annealed
1045	0.44	0.87	0.34	0.043	0.043	....	....	Cu 0.09	Not known
1055*	0.56	(0.19)	0.04	tr	0.023	....	....	Cu 0.02	Annealed
1055*	0.56	(0.30)	0.18	0.016	0.034	....	....	Cu 0.09	Not known
X1055	0.59	0.92	0.25	0.024	0.033	....	....	....	Annealed
1060*	0.64	(0.27)	0.06	0.010	0.028	....	....	Cu 0.09	Not known
1065	0.68	0.72	0.18	0.028	0.016	....	....	....	Roller
1065*	0.65	(0.12)	0.09	0.01	0.03	....	....	Cu 0.03	Annealed
1075	0.76	0.69	0.21	0.026	0.024	....	....	....	Roller
1075*	0.75	(0.35)	0.10	0.010	0.018	....	....	Cu 0.07	Not known
1080*	0.80	(0.30)	0.10	0.012	0.016	....	....	Cu 0.08	Not known
1080*	0.81	(0.10)	0.06	tr	0.025	....	....	Cu 0.02	Annealed
1095	0.94	0.35	0.13	0.016	0.018	....	....	Cu 0.08	Not known
1095	1.02	0.36	0.08	0.013	0.014	....	....	Cu 0.05	Not known
Nickel Steel									
2330*	0.33	0.78	(0.09)	0.014	0.035	3.59	....	....	Annealed
Nickel-Chromium Steels									
3145	0.40-0.50	0.50-0.80	....	< 0.04	< 0.045	1.00-1.50	0.45-0.75	....	Quenched and tempered
3150*	(0.43)	0.78	....	0.015	0.027	(1.87)	0.75	....	Quenched and tempered
3250*	0.50	(0.64)	0.15	0.015	0.031	1.90	(0.88)	....	Quenched and tempered
3335	0.32	0.53	0.23	0.013	0.015	3.53	1.37	....	Quenched and tempered
Molybdenum Steel									
4140	0.39	0.51	0.19	0.015	0.029	....	0.87	Mo 0.21	Roller
Chromium Steels									
5140*	0.40	0.78	(0.57)	0.011	0.015	....	0.78	....	Quenched and tempered
5150*	(0.60)	....	....	....	....	....	1.00	....	Not known
Chromium-Vanadium Steels									
6115*	0.12	(0.05)	(0.85)	0.020	0.040	....	0.85	V 0.23	Annealed
6135	0.34	0.72	0.17	0.009	0.010	....	0.96	V 0.17	Quenched and tempered
6140*	0.40	0.76	0.14	0.006	0.012	..	(1.20)	V 0.17	Quenched and tempered
Tungsten Steels									
71360*	0.64	0.01	(0.05)	0.015	0.012	....	3.73	{ W 14.08 V 0.11 }	Not known
71360*	(0.73)	...	....	....	....	....	3.90	{ W 13.50 W 14.63 }	Not known
71360*	(0.82)	0.26	0.18	0.003	0.016	3.71	{ Mo 0.17 V 0.20 }	Not known
71660*	0.66	0.08	(0.08)	0.018	0.016	3.43	{ W 16.81 V 0.11 }	Not known

(Continued)

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^bEach S.A.E. number marked * indicates that the chemical composition is not strictly in accordance with the S.A.E. specification.

Coefficients of Linear Expansion of S.A.E. Steels—Cont.

Average Coefficients of Expansion per Degree Centigrade ^d											Observer ^e
15-75°C. 59-167°F.	20-100°C. 68-212°F.	20-200°C. 68-392°F.	20-300°C. 68-572°F.	20-400°C. 68-752°F.	20-500°C. 68-932°F.	20-600°C. 68-1112°F.	20-700°C. 68-1292°F.	20-800°C. 68-1472°F.	20-900°C. 68-1652°F.	20-1000°C. 68-1832°F.	
×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	
....	11.6	12.5	13.0	13.6	14.2	14.6	15.0	....	....	....	Driesen ¹
11.9	....	....	....	....	....	....	....	....	....	....	Honda ²
....	11.9 ^f	12.5	13.0	13.6	14.2	....	....	....	....	....	Schad ³
12.1	....	....	....	....	....	....	....	....	....	....	Honda ²
....	11.7	12.1	12.8	13.4	13.9	14.4	14.8	....	....	....	Driesen ¹
....	12.5 ^f	13.4	14.2	15.1	....	....	....	....	....	....	Peters ⁴
11.7	....	....	....	....	....	....	....	....	....	....	Honda ²
....	11.1	11.9	12.7	13.4	14.0	14.4	14.8	....	....	....	Driesen ¹
....	9.4 ^g	10.9	12.1	13.0	13.7	14.3	14.7	....	....	....	Souder and Hidnert ⁵
....	11.3	12.0	12.5	13.3	13.9	14.4	14.8	....	....	....	Driesen ¹
....	11.1 ^g	11.7	12.7	13.5	14.0	14.3	14.7	....	....	....	Souder and Hidnert ⁵
11.6	....	....	....	....	....	....	....	....	....	....	Honda ²
12.1	....	11.0	11.8	12.6	13.4	14.0	14.5	14.8	....	....	Driesen ¹
....	11.1 ^g	11.9	12.9	13.5	14.1	14.6	14.9	....	....	....	Honda ²
11.8	....	....	....	....	....	....	....	....	....	....	Souder and Hidnert ⁵
....	11.8 ^f	12.6	13.3	14.0	....	....	....	....	....	....	Souder and Hidnert ⁵
....	11.0	11.6	12.3	13.2	13.8	14.2	14.6	....	....	....	Driesen ¹
....	11.5 ^f	12.3	13.0	13.8	....	....	....	....	....	....	Souder and Hidnert ⁵
11.6	....	....	....	....	....	....	....	....	....	....	Honda ²
11.7	....	....	....	....	....	....	....	....	....	....	Honda ²
....	11.0	11.6	12.4	13.2	13.8	14.2	14.7	....	....	....	Driesen ¹
11.5	....	....	....	....	....	....	....	....	....	....	Honda ²
11.5	....	....	....	....	....	....	....	....	....	....	Honda ²
....	10.9 ^g	11.2	12.1	12.9	13.4	13.8	....	....	....	....	Souder and Hidnert ⁵
....	11.8 ^f	12.3	12.9	13.4	14.0	....	....	....	....	....	Westinghouse Electric & Mfg. Co. ⁷
....	12.0 ^g	....	12.9 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	11.7 ^g	....	12.7 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	11.8 ^g	....	12.8 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	11.2 ^f	11.8	12.4	13.0	13.6	....	....	....	....	....	Schad ³
....	12.8 ^g	....	13.8 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	(11.3×10 ⁻⁶ , 50 to 150°C.; 14.8×10 ⁻⁶ , 450 to 550°C.)	....	....	....	....	....	....	....	....	....	Matsushita ⁹
....	11.6 ^g	12.1	12.7	13.2	13.6	14.0	14.3	....	....	....	Souder and Hidnert ⁵
....	11.8 ^g	....	13.1 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	11.6 ^g	....	13.0 ^h	....	....	....	....	....	....	....	Hidnert ⁸
....	(11.1×10 ⁻⁶ , 50 to 150°C.; 13.9×10 ⁻⁶ , 550 to 650°C.)	....	....	....	....	....	....	....	....	....	Honda ²
....	(10.7×10 ⁻⁶ , 50 to 150°C.; 14.3×10 ⁻⁶ , 550 to 650°C.)	....	....	....	....	....	....	....	....	....	Honda ²
....	(10.0×10 ⁻⁶ , 50 to 150°C.; 14.1×10 ⁻⁶ , 550 to 650°C.)	....	....	....	....	....	....	....	....	....	Honda ²
....	(10.8×10 ⁻⁶ , 150 to 250°C.; 13.6×10 ⁻⁶ , 550 to 650°C.)	....	....	....	....	....	....	....	....	....	Honda ²

(Continued)

^aEach value in parenthesis indicates that it lies outside the range of the S.A.E. specification.^bTo obtain corresponding coefficients of expansion per °F., multiply the coefficients in this table by 5/9.^cThe superior numbers refer to the references at the end of the table.^dCoefficients of expansion on this line, from 0°C. or 32°F. instead of 20°C. or 68°F.^eCoefficients of expansion on this line, from 25°C. or 77°F. instead of 20°C. or 68°F.^fFrom 25-270°C. (77-518°F.).

Coefficients of Linear Expansion of S.A.E. Steels—Cont.

Chemical Composition,^c %

S.A.E. No. ^b	C	Mn	Si	P	S	Ni	Cr	Misc.	Treatment
Corrosion and Heat Resisting Alloys									
30905	0.06	0.36	0.28	0.016	0.012	9.6	17.7	.....	Quenched from 1,975°F.
	0.07	....	0.45	.....	.....	8.93	17.35	.....	Quenched from 2000°F.
	0.07	0.59	0.47	0.013	0.003	9.12	18.08	{ Ti 0.38 } { Al 0.06 }	Annealed
30915	0.10	....	....	.....	.....	8.0	18.0	.....	Heated 336 days at 500°C.
	0.12	0.41	0.37	0.017	0.016	8.9	17.5	.....	Hot rolled and annealed
	0.14	0.45	0.28	.....	.....	7.80	17.28	{ Al 0.18 } { Cu 0.14 }	Hot rolled and annealed
30915*	(0.21)	0.24	(0.89)	.....	.....	9.7	18.7	.....	Forged and annealed
51210	0.09	0.43	0.33	0.009	0.016	0.06	12.0	.....	Annealed
	0.09	0.56	0.31	0.010	0.010	0.39	12.3	.....	Annealed
	0.09	0.60	0.57	0.011	0.007	0.19	12.0	.....	Annealed
X51410*	0.13	0.56	0.35	0.031	(0.019)	.....	13.5	.....	Annealed
51335	0.30	0.18	0.11	0.020	0.011	.....	13.10	.....	Hardened
	0.30	0.18	0.11	0.020	0.011	.....	13.10	.....	Annealed
	0.30-0.40	....	...	.....	.....	.....	13.00	.....	Annealed
51510	0.12	0.39	....	0.016	0.013	0.09	15.9	.....	Annealed
	0.04	0.29	0.28	0.021	0.021	0.08	17.6	.....	Annealed
	0.07	0.48	0.45	0.018	0.008	.....	16.43	.....	Sheet bar as received
51710	0.13	0.16	0.25	0.01	0.01	.....	16.4	.....	Quenched and tempered
	0.04	0.28	(0.62)	.....	.....	.....	17.04	{ Al 0.08 } { Cu 0.14 }	Hot rolled
	0.06	0.45	(0.58)	.....	.....	.....	17.08	Al 0.08	Annealed

Coefficients of Linear Expansion of S.A.E. Steels—Cont.

Average Coefficients of Expansion per Degree Centigrade ^a											Observer ^b
15-75°C. 59-167°F.	20-100°C. 68-212°F.	20-200°C. 68-392°F.	20-300°C. 68-572°F.	20-400°C. 68-752°F.	20-500°C. 68-932°F.	20-600°C. 68-1112°F.	20-700°C. 68-1292°F.	20-800°C. 68-1472°F.	20-900°C. 68-1652°F.	20-1000°C. 68-1832°F.	
×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	×10 ⁻⁶	
16.5	17.2	17.7	18.1	18.3	18.6	19.0	19.5	19.7	20.0	Hidnert ¹⁰	
17.2 ^c	17.4	17.8	18.1	18.4	18.7	18.9	....	....	....	Austin and Pierce ¹¹	
16.7 ^c	17.2	17.6	18.1	18.5	18.8	....	....	....	....	Austin and Pierce ¹¹	
17.7 ^c	18.0	18.2	18.6	19.0	19.2	....	....	....	....	Austin and Pierce ¹¹	
16.4	....	17.2	17.6	17.8	18.2	18.5	18.7	....	....	Hidnert ¹⁰	
16.4	17.0	17.7	18.2	18.6	19.0	....	....	....	....	Hidnert ¹⁰	
16.0	16.7	17.3	17.7	18.0	18.4	18.7	19.1	19.5	20.0	Hidnert ¹⁰	
....	10.2	....	11.2	....	12.0	....	....	....	....	Hidnert and Sweeney ¹²	
9.8	10.4	10.8	11.2	11.6	12.1	....	....	....	....	Hidnert and Sweeney ¹²	
10.2	10.5	10.9	11.3	11.6	11.9	....	12.3	....	....	Hidnert and Sweeney ¹²	
10.2	10.5	10.9	11.3	11.7	12.1	....	12.6	....	....	Hidnert and Sweeney ¹²	
9.8	9.8	....	9.8	10.6	11.2	....	11.8	....	....	Souder and Hidnert ¹³	
10.3	10.7	11.3	11.5	11.8	12.1	12.4	12.5	....	....	Souder and Hidnert ¹³	
10.0 ^c	10.4	11.0	11.4	11.8	12.2	12.4	....	....	....	Souder and Hidnert ¹³	
....	....	10.8	....	....	11.8	....	....	....	....	Hidnert and Sweeney ¹²	
10.1	10.4	10.7	11.1	....	11.6	11.8	12.2	12.8	....	Hidnert ¹⁰	
10.7 ^c	11.2	11.5	11.8	12.1	12.3	12.5	....	....	....	Austin and Pierce ¹¹	
9.9	10.1	....	10.9	11.3	11.7	....	12.4	....	....	Hidnert and Sweeney ¹²	
10.6	10.8	11.1	11.4	11.7	11.9	12.1	12.5	13.1	Hidnert ¹⁰	
10.3	10.6	11.0	11.2	11.4	11.6	11.8	12.4	12.9	Hidnert ¹⁰	

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Magnetically Soft Materials

By T. D. Yensen*

Introduction—Several conflicting characteristics are often required in magnetically soft materials. For this reason a number of different magnetic alloys ranging from pure iron through the silicon irons to the high nickel-iron alloys have been developed. The characteristics of importance are: (1) Hysteresis loss on passing through a magnetic cycle and arising from internal magnetic "friction." This should be low. (2) Eddy current loss due to electric currents induced in the material by changes in flux. This should be low. (3) Magnetic permeability should be high and sometimes must be high or constant at low field strengths. (4) Saturation value should be as high as other considerations permit. (5) In special applications a definite change in permeability with temperature is required. (6) The cost, availability and ease of processing are important.

Effect of Impurities—As the ferromagnetic properties are a function of the regularity of the space lattice, it follows that anything that affects this regularity will also affect the magnetic properties. Impurities like carbon, sulphur, nitrogen, and oxygen are particularly harmful, because when in solution they occupy interstitial spaces in the crystal lattice and very small amounts therefore produce large effects.¹ Furthermore, as the solubility is low at room temperature, the

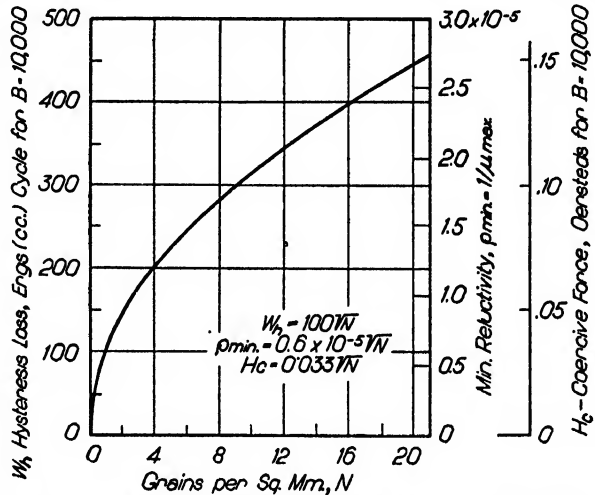


Fig. 1—Net effect of grain size on hysteresis loss of pure iron.

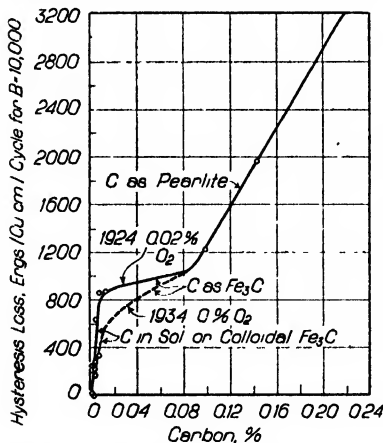


Fig. 2a—Effect of carbon on the hysteresis loss of iron.

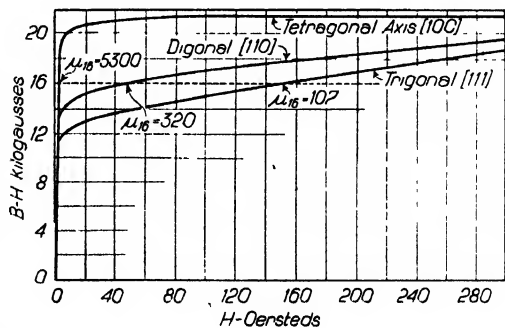


Fig. 2—Effect of grain orientation on the B-H properties of iron (Honda and Kaya).

excess amount is slowly precipitated in the form of small particles inside the grains with even greater disturbing effect, usually referred to as "aging." Carbon especially should be kept low in iron and iron-silicon alloys in order to obtain low hysteresis loss and high maximum permeability. The amount should not be over 0.01% and

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preferably less than 0.005%. Fig. 2a shows the effect of carbon on the hysteresis loss of iron. Sulphur and oxygen should likewise be held down to similar values.

Effect of Grain Size—Because of the disturbances at the grain boundaries, the fewer the grain boundaries the better are the magnetic properties, which is another way of saying that the grain size should be as large as possible with the single crystal as the limit, Fig. 1.

Effect of Grain Orientation—Almost all ferromagnetic materials are magnetically anisotropic, that is they have different magnetic properties in the different crystallographic orientations. This is shown in Fig. 2 for iron² and in Fig. 3 for an iron-silicon alloy with 3.85% Si.³ In both of these cases the direction parallel to a cube edge [100] is the one having the highest permeability. In other cases this is not so, for example, in Ni the situation is just the reverse: The direction of easy magnetization is that of the body diagonal [111]. So in all cases crystal orientation should be taken into account in controlling the magnetic properties of ferromagnetic materials.

Effect of Alloying Elements—While pure iron may in many respects be regarded as the ideal ferromagnetic material, it has certain drawbacks that makes it unsuitable for practical use especially in a.c. circuits. The resistivity is low, necessitating rolling the iron very thin to keep eddy currents down, and when this is done, the magnetic properties are poor. One of the main objects

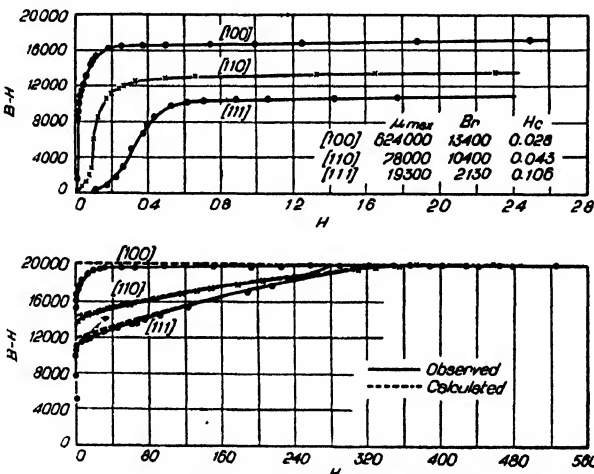


Fig. 3—The observed and calculated magnetization curves for the [100], [110] and [111] directions of single crystals of 3.85% silicon iron (Williams).

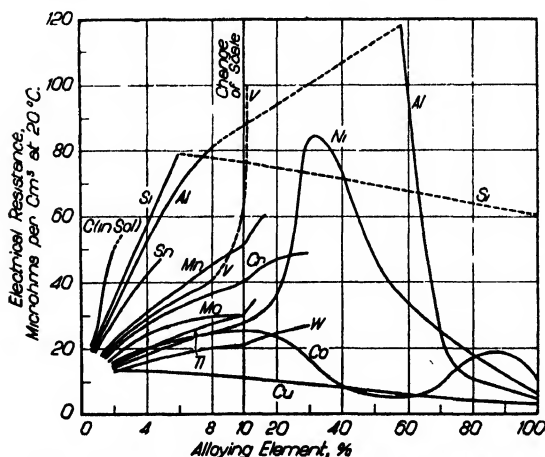


Fig. 4—Effect of elements on the electrical resistance of iron (Stablein and Yensen).

of alloying elements is therefore to raise the electrical resistivity of iron so as to enable us to use it to advantage in a.c. circuits (which means perhaps 75% of all applications of magnetic materials in industry). Fig. 4 shows how the various elements affect the resistivity of iron. Outside of carbon in solution, silicon and aluminum increase the resistivity more than any other element.

These two elements also have another important effect: They eliminate the allotropic transformations in iron, so that the alloys can be annealed at high temperatures without recrystallization on cooling, thus permitting large grains. Both these elements are substitution elements and for this reason can be added to iron in fairly

large quantities without affecting seriously the magnetic properties, although they do reduce the saturation value. However, more than 4.5% silicon or 8% aluminum makes iron too brittle for most commercial use.

Another reason for keeping the alloying elements down to low values is that all elements, with the exception of cobalt, lower the saturation value of iron, Fig. 5.

The chief difficulty in connection with silicon and aluminum is that they form stable oxides, so that if the iron is not thoroughly deoxidized before adding the alloying elements, oxide inclusions are formed that cannot again be eliminated and have deleterious effects on the magnetic properties. Aluminum is particularly bad in this respect.

Unsuspected and valuable magnetic properties are obtained by combining iron with nickel or with nickel and cobalt and by adding to these combinations other elements like copper, molybdenum, or chromium, as will be seen later.

Magnetic Materials—Iron—

By careful preparation of a single crystal of iron Cleffi has obtained a maximum permeability of 1,430,000 and Ziegler and Yensen² have prepared ring samples of iron having a hysteresis loss of 70 ergs per cc. per cycle for $B = 10,000$.

For experimental uses iron can now be obtained with a purity of 99.95% or better, having magnetic properties as shown in Fig. 6: Maximum permeability of about 100,000 and a hysteresis loss for $B = 10,000$ of about 100 ergs per cubic cm. per cycle (Wemco iron).

The latest saturation value of iron comes from the Physikalisch-Technische Reichsanstalt³ and is given as:

$$4\pi I_s = 21,580 \pm 10 \text{ gauss}$$

based on a density of 7.878.

These values agree well with those given by Cleaves and Thompson.¹ The electrical resistivity given by Cleaves and Thompson as the most reliable value is 9.8 microhms per cubic cm. at 20°C. with a temperature coefficient of 0.0065 per °C.

Iron-Silicon Alloys—Although pure iron may in many respects be regarded as the ideal magnetic material, it is easier to obtain good magnetic properties in iron by the use of a small amount of silicon than without it.^{11, 12} Brittleness imparted by the silicon limits the amount in practice to about 4.5%, although 6% may be used for special purposes.

See the article in this Handbook for further information on iron-silicon alloys.

Fe-Al and Fe-Al-Si Alloys—

While aluminum is known to have about the same effect on iron as silicon, both as to electrical resistivity

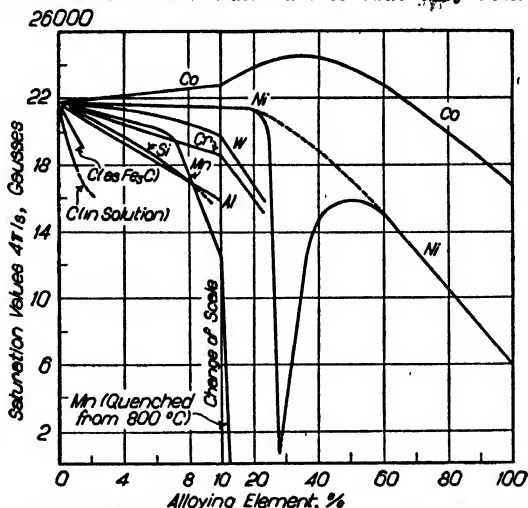


Fig. 5—Effect of elements on the saturation values of iron (Stablein and Yensen).

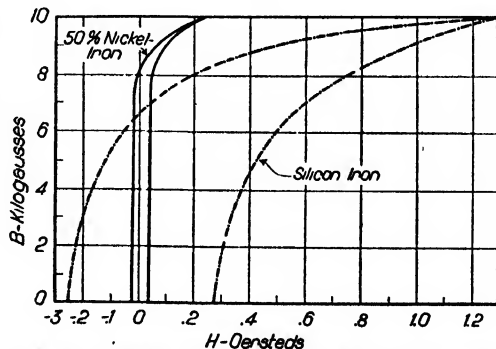
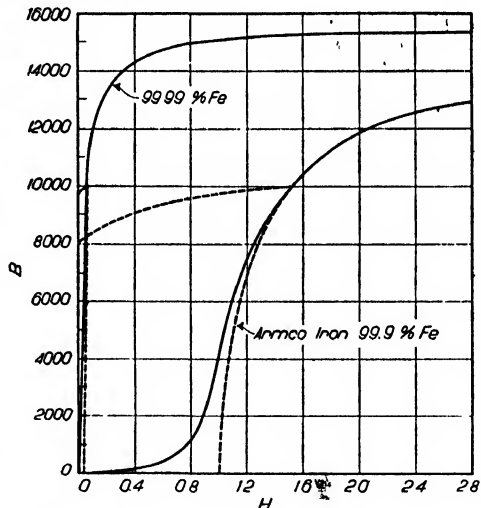


Fig. 6—(Upper) Hysteresis loops and B-H curves for nearly pure iron. (Lower) Hysteresis loop of Hipernik in comparison with silicon iron.

and magnetic properties,⁹ it has never become a serious competitor on account of the difficulties in connection with the manufacturing processes. Ternary alloys of iron, silicon and aluminum have recently been investigated by Masumoto.¹⁰ The alloy contained 8-11% silicon and 5-6.5% aluminum and is reported to have an initial permeability up to 35,000, a maximum permeability up to 162,000 and a hysteresis loss down to 28 ergs for $B = 5,000$. With such high silicon and aluminum contents the saturation value is necessarily low ($4\pi I_s = 11,000$). The alloys are brittle.

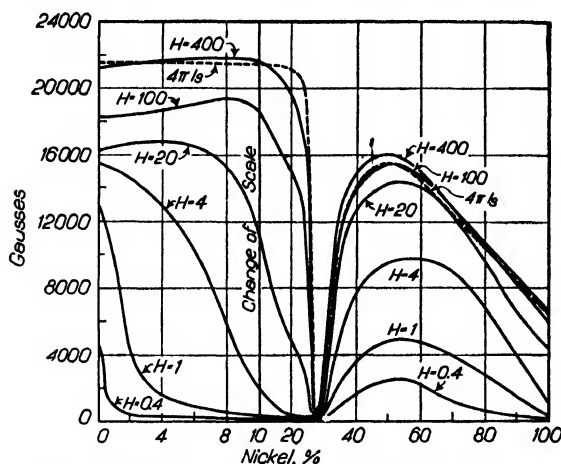


Fig. 7—Saturation intensity of iron-nickel alloys. Electrolytic iron and nickel, melted and annealed in vacuum. From 0.5-1% Mn added to alloys with more than 30% nickel to facilitate forging.

nickel that had unusually good magnetic properties. At still lower magnetizing forces, the optimum composition has been found to be in the region of 70-85% nickel.

While these alloys are basically iron-nickel alloys, appreciable percentages of other elements are added in many cases to develop or accentuate some particular characteristic which is desirable for the application in view.

The trade names,¹¹ approximate composition and applications of the most important iron-nickel alloys are given in Table I.

Annealed iron-nickel alloys containing between 30-90% nickel have initial permeabilities higher than that of Armco iron. Alloys containing more than 50% nickel are sensitive to heat treatment as shown in Fig. 8. The heat treatment that improves initial and maximum permeability consists in air quenching thin strips on a copper block from the magnetic transformation point. The most startling results were obtained for alloys in the neighborhood of 80% nickel (the best composition being 78½%), and the name "Permalloy" was given to the alloys in this range. Maximum permeabilities of 100,000 are readily obtained with this alloy (Fig. 9) but the saturation value is low (11,000) and its electrical resistivity is only about double that of iron. However, it was later found that the resistivity could be markedly increased by the addition of chromium or molybdenum, which at the same time eliminates the necessity for air quenching and increases the initial permeability to over 20,000, but at a further sacrifice of saturation value.¹² Table II gives the principal characteristics of the important alloys in this group, together with Armco iron and other alloys.

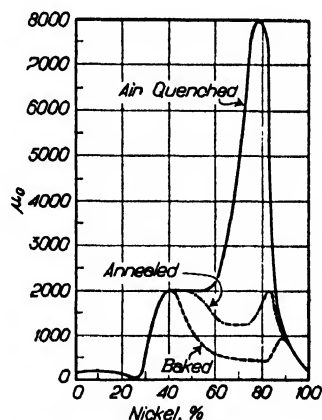


Fig. 8—Initial permeabilities of the iron-nickel series (Elmen).

⁹In the preparation of this section liberal use has been made of Data Sheet No. 2, "Iron-Nickel Alloys for Magnetic Purposes," prepared by J. W. Sands, of The International Nickel Co., Inc., for their Iron Nickel Data Book (1938).

T. D. Yensen: Franklin Inst. Centenary Celebration, Sept. 19, 1924. J. Franklin Inst., 1925, v. 199, p. 323.

Table I
Commercial Magnetic Iron-Nickel Base Alloys

Name	Per cent Nickel	Sponsor
<i>Alloys With Very High Permeability at Low Field Strengths</i>		
Permalloy	30-90 + special heat treatment and some-times + Cr or Mo	Western Electric Co.
Mumetal	Approx. 78 + 6% Cu and 1.5% Cr	Telcon* and Allegheny-Ludlum Steel Co.
Permafay	Approx. 80	Acieries de Firminy
1040 Alloy	72 + 14% Cu and 3% Mo	Heraeus Vacuumschmelze
<i>High Permeability Alloys for Higher Field Strengths</i>		
Megaperm 6510	65 + 10% Mn	Heraeus Vacuumschmelze
Hipernik	50	Westinghouse E. & M. Co.
Hyperm	50	Krupp
Nicaloi	49	General Electric Co.
Audiolloy	48	Crucible Steel Co.
Permenorm	48	Heraeus Vacuumschmelze
Allegheny Electric Metal	47	Allegheny-Ludlum Steel Co.
Anhyster O and D	45-50	Acieries d'Imphy
Radiometal	45-50	Telcon*
2129	45-50	Telcon*
Megaperm 4510	45 + 10% Mn	Heraeus Vacuumschmelze
<i>Moderately High Permeability Alloys of High Electrical Resistance</i>		
Rhometal	40-45 + 5% Cr and 3% Si	Telcon*
Gamma	Approx. 35	Acieries d'Imphy
Anhyster A and B	Approx. 35	Acieries d'Imphy
<i>Alloys With Constant Permeability Over a Range of Flux Densities</i>		
Perminvar	20-75 + 5-40% Co + special heat treatment and sometimes + Mo	Western Electric Co.
Conpernik	50 + special heat treatment	Westinghouse E. & M. Co.
Isoperm	40-55 + special treatment	Allgemeine Elektrizitäts-Gesellschaft
Isoperm (precipitation types)	36-50 + 9-15% Cu	Allgemeine Elektrizitäts-Gesellschaft
	40-60 + 3-4% Al	Allgemeine Elektrizitäts-Gesellschaft
<i>Alloys with Permeability Varying with Temperature</i>		
Compensator Alloy	29-32.5	Simonds Saw & Steel Co.
N30	30	Carpenter Steel Co.
Thermoperm	30	Krupp
N. M. H. G.	30	Acieries d'Imphy

*Telegraph Construction & Maintenance Co., Ltd., London, England.

Table II
Magnetic Properties of Various Alloys

Material ^a	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cc. per cycle ^a	Residual Induction, gauss	Coercive Force, oersteds	Saturation value, gauss ^b	Resistivity, microhm cm
Armco iron	250	7,000	5,000	13,000	1.0	22,000	11
4% Silicon-iron	600	6,000	3,500	12,000	0.5	20,000	50
78.5 Permalloy, quenched	10,000	105,000	200	6,000	0.05	10,700	16
48 Permalloy	2,700	23,000	1,200	8,000	0.3	16,000	45
3.8-78.5 Cr-Permalloy	12,000	62,000	200	4,500	0.05	8,000	65
3.8-78.5 Mo-Permalloy	20,000	75,000	200	5,000	0.05	8,500	55
45-25 Perminvar, baked	400	2,000	2,500	3,000	1.2	15,500	19
7-45-25 Mo-Perminvar, baked	550	3,700	2,600	4,300	0.65	10,300	80
70-7.5 Perminvar, annealed	750	3,500	.....	.....	.8	12,000	16

^aSingle numbers preceding the word "Permalloy" signify the nickel content, and double numbers signify first the content of chromium or molybdenum, and second the nickel content, the balance being iron in each case. The two large numbers before "Perminvar" indicate the nickel and cobalt contents, respectively, and the small initial number indicates the molybdenum content.

^bFor saturation value of the flux density.

^cSaturation value of the intrinsic induction.

50% Nickel-Iron Alloys—The alloys in the region of 50% nickel exhibit nothing remarkable (Fig. 7) except that their saturation values are the highest of all iron-nickel alloys above 30% nickel. By ordinary pot annealing a maximum permeability of 20,000-25,000 can be obtained with an initial permeability of 2,700, if pure material is used. Such an alloy is 45% nickel listed in Table II, the permeability curve of which is shown in Fig. 9.

The magnetic properties of these alloys can be vastly improved by annealing them in dry hydrogen at a temperature of 1000-1200°C. for several hours.¹³ This treatment reduces carbon, sulphur and other impurities, but particularly oxygen. In its improved form this alloy has been given the name "Hipernik" (from high permeability nickel). The nickel content is not particularly critical, it may be varied from 40-60%, but for highest saturation value it should be kept close to 50%, see Fig. 6.

The use of this alloy in place of ordinary 4% silicon iron for transformer cores would result in a reduction of energy losses to about one-half. However, because of its high cost, its use is limited to special transformers, such as current transformers in which, because of its high permeability and low loss, the ratio errors and phase angle deviations are reduced to negligible quantities. Cold rolled in the form of continuous ribbon, this alloy is particularly suitable for bushing type of current transformers, as in this way there is no waste of material.

While this 50% Ni alloy cannot compete with the higher nickel alloys for applications requiring the highest initial permeability, it is preferable for most other uses, because of its higher saturation value (Fig. 7).

In Table III are listed the magnetic properties of this alloy in comparison with values of other alloys.

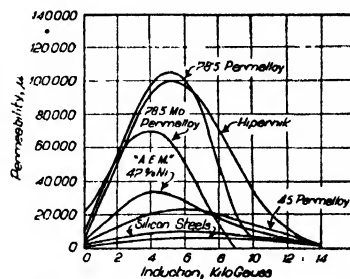


Fig. 9—Permeability curves for various magnetic alloys (Wise).

Table III

Magnetic Properties of 50% Nickel-Iron Alloys in Comparison with Other Alloys

(In accordance with information obtained from the manufacturers)

Material	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cc. per cycle ^a	Residual Induction, gauss ^b	Coercive Force, oersteds ^a	Saturation Value, gauss ^b	Resistivity, Microhm-cm.	Form of Sample	Specific Gravity
Wemco Iron (99.95% Fe) . . .		100,000	150	9,000	0.05	21,600	10	Solid ring	7.9
4-4.5% Silicon Iron	500	12,000	800	6,000	0.3	19,500	55	.014 in. sheet	7.6
Hipernik	4,500	100,000	100	8,000	0.03	16,000	45	.014 in. sheet	8.3
45 Permalloy . . .	2,700	23,000	1,200 ^b	8,000 ^b	0.3 ^b	16,000	45	.....	...
Allegheny Electric Metal . .	5,000	32,500	718	5,500	0.1	16,000	45	.....	8.3

^aFor B = 10,000 except as noted.
^bFor B = 16,000.

Miscellaneous—Numerous modifications have been made in these alloys by the addition of other elements and by variation in the heat treatments. They are made by various companies here and abroad, the most important of which are listed in Table IV.*

By cooling some of these alloys in a magnetic field through the magnetic transformation point, great improvements have been obtained.¹⁴ Particularly good results were obtained with 65% Ni and with 45% nickel, 30% iron, 25% cobalt. A maximum permeability of over 600,000 was reported for the 65% nickel alloy. The cause of the improvement is explained on the basis of elimination of strains due to magnetostriction.

*Prepared by J. W. Sands and T. D. Yensen from data obtained from Aciéries d'Imphy, Telegraph Construction and Maintenance Co.

Materials with High Magnetic Saturation Value—Iron has a saturation value of 21,600 ($4\pi I_s$). To exceed this value, it is necessary to alloy iron with cobalt in amounts between 0 and 65%. The highest value is obtained by using 34.5% cobalt.

Table IV
Magnetic Properties of Some Foreign Magnetic Alloys

Material ^a	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cc. per cycle (B = 5,000)	Coercive Force, oersteds (B = 5,000)	Saturation value, gauss	Resistivity, microhm cm.	Specific gravity
Mumetal	10-30,000	60-100,000	40-60	0.03	6-9,000	42	8.6
Radiometal	2,000	10-15,000	350	0.4-0.5	15,600	55	8.3
Anhyster B	1,300	.....	...	...	9,000	70	..
Anhyster C	1,500	.....	...	...	13,000	59	..
Anhyster D	2,200	25,000	330	...	15,000	46	..
1040 Alloy.....	Up to 50,000	100,000	50	...	6,000	56	..
Permenorm 4801 ^b	2,700	19,000	...	0.20	14,000	58	..
Megaperm 6510..	4,800	26,000	...	0.08	8,500	58	..
Rhometal	850	5,000	420	...	4,500	..	..

^aSee Table I for chemical compositions.

^bConstant permeability of over 2,000 for $H < 0.06$.

The saturation value of 24,200 is regarded as well established (Fig. 5) for 34.5% cobalt-iron, corresponding to Fe_2Co .

A 50% cobalt alloy according to Elmen¹⁷ with the addition of a small amount of vanadium is easy to forge and roll and because of its better magnetic properties below $H = 200$, it is preferable to the 34.5% alloy where cost is of no importance. The name "Permendur" has been applied to this alloy.

Materials with Constant Permeability—At the Bell Laboratories were developed

certain iron-nickel-cobalt alloys¹⁸ having a constant permeability at low magnetizing forces. These, containing in the neighborhood of 30% iron, 45% nickel, and 25% cobalt were called "Perm-Invar." They are useful wherever a constant inductance or reactance is essential such as in filter coils for radio circuits or for loading coils for telephone circuits, where air gaps are otherwise used with sheet materials. Fig. 10 shows the hysteresis loops for the optimum composition. Similar (but not so good) results may be obtained with 50% iron-nickel alloys by means of a special heat treatment which, in fact, is an incomplete annealing below 800°C .¹⁹

A more recent development²⁰ in Germany resulted in iron-nickel alloys called "Iso-perms" containing 35-55% nickel. Aluminum, copper, beryllium, manganese, and titanium have been used with varying success. The best alloy contains 40-45% nickel, 45-50% iron, and 5-15% copper. The alloy is first drastically cold rolled, then quenched from a high temperature, further cold rolled, and finally annealed, a treatment by which the copper is precipitated in such a way as to produce a preferred arrangement of the iron-nickel lattice, resulting in low retentivity and constancy of permeability (50-60)

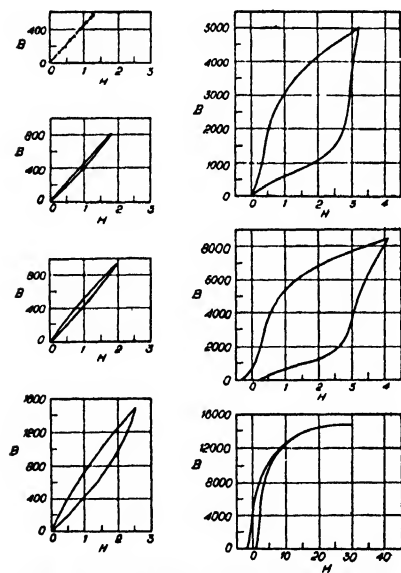


Fig. 10—Hysteresis loops for alloy containing 45% nickel, 25% cobalt, and 30% iron—annealed.

over a wide range of H (0-100 oersteds).

Alloys for Magnetic Temperature Compensation—Because of the fact that the magnetic permeability of iron and iron alloys decreases with temperature (except for low values of H) the reading of electrical meters that depends upon the flux produced by a constant voltage supply or by a certain load current, such for example as watt-hour meters, decreases with the ambient temperature. To compensate for

such errors it is customary to shunt a certain amount of the magnetic flux around the moving part of the meter by means of an alloy having an unusually high magnetic temperature coefficient between 0 and 100°C., so that, as the ambient temperature increases, the amount of the shunted flux decreases, forcing more of the flux through the moving member than otherwise would be the case. By proper proportioning of the parts, it is thus possible to compensate almost completely for the temperature changes. Alloys for such purposes are essentially of two types:

(1) The nickel-copper type having a composition around 70% nickel, 30% copper with certain admixtures, such as 2% iron (Calmalloy²¹); or with about 1% manganese with or without a small amount of silicon (Westinghouse Alloy²²).

Characteristic curves are shown for these alloys in Fig. 11.

(2) The nickel-iron type containing around 30-40% nickel with a small amount of Mn, Cr and Si. Curves for this type alloy are shown in Fig. 12. All values of H from low temperatures up to 60°C. are nearly straight lines and higher temperature coefficients than for the 70% nickel-30% copper type of alloy.

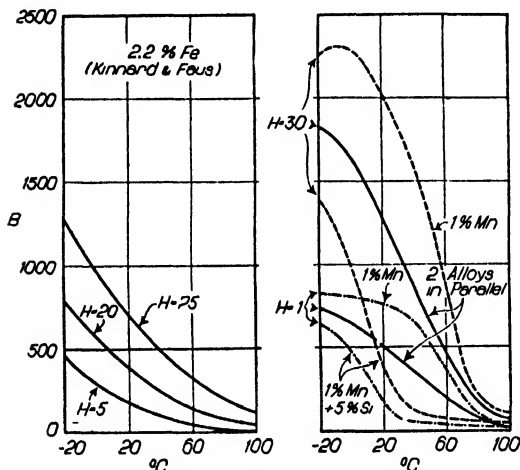


Fig. 11—Magnetic temperature compensators for 70% nickel-30% copper type alloy with modification in composition as shown; Left, Calmalloy, Right, Westinghouse Alloy.

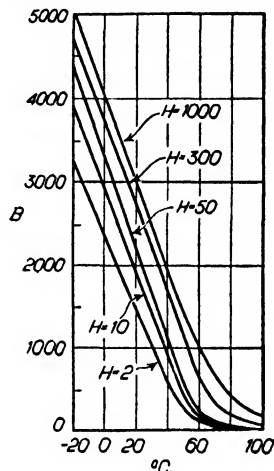


Fig. 12—30% nickel type of magnetic temperature compensators (Thermoperm Alloy) (Stablein).

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Permanent Magnet Alloys

By K. L. Scott*

Introduction—This article was written during a period of great development activity in the field of permanent magnet alloys. As a result of this activity, there are commercially available two distinct types of materials for making permanent magnets; namely, the older and well known types of magnet steel, and the new, precipitation hardening alloys. There is a possibility that compressed metallic oxide magnets may be added as a third type.

Theory of Permanent Magnets—In order to understand the relative importance and usefulness of each type of material, a brief resumé of the fundamental theory of permanent magnets will be given. In Fig. 1 is shown a typical hysteresis loop and magnetization curve for a permanent magnet alloy. The variables are

magnetizing force, H , in Gilberts per cm. ($\frac{4-\pi}{10}$ —times ampere turns per cm.) as

abscissae and magnetic flux density, B , in gauss (so-called "lines of force" per sq.cm.) as ordinates. Starting with an unmagnetized specimen, if increasing values of H are applied (as by gradually increasing the electric current in a coil of wire wound on the specimen) the corresponding values of magnetic flux produced in the specimen will be as shown by the normal induction curve. If now the values of H be gradually reduced from the highest applied value, H_{max} , to zero and then increased in the negative direction to a negative H_{max} (accomplished by reversing the current in the magnetizing winding), the value of B will change from a positive B_{max} to a negative B_{max} along the left-hand curve of the hysteresis loop. If this process be repeated, starting with a negative H_{max} , the right-hand side of the hysteresis loop will be traced. If the value of magnetizing force be reduced from H_{max} to zero (as by opening the circuit of the magnetizing winding) the value of B will drop from B_{max} to the intersection of the hysteresis loop with the B axis. The value of B at the point of intersection is called the residual induction, designated B_r . If there is now applied sufficient negative magnetizing force to reduce the value of B from B_r exactly to zero, the value of negative H required will be as shown by the intersection of the hysteresis loop with the

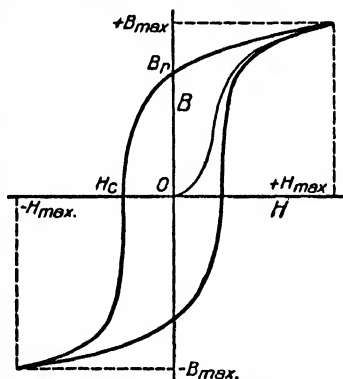


Fig. 1—Typical hysteresis loop of permanent magnet alloy.

H axis. This particular value of H is called the coercive force, designated H_c . The descending branch of the hysteresis loop between the points B_r and H_c is most important in permanent magnet theory. It is known as the demagnetization curve. If the product of the coordinates, B and H , of this curve are plotted against corresponding values of B , a new curve is obtained, as shown in Fig. 2. The maximum value of the product $B \times H$, designated $(BH)_{max}$, as obtained from this curve, is proportional to the maximum amount of magnetic energy which a magnet of the given material can support in an air gap, per unit volume of material in the magnet. Hence, the most efficient magnet design will be one which works the magnet at the flux density corresponding to the $(BH)_{max}$ point of the material.

It is not necessary to plot the curve of $B \times H$ against B to determine the value of $(BH)_{max}$, or the corresponding value of B . The coordinates of the $(BH)_{max}$ point are determined to a close approximation by the intersection of the diagonal of the rectangle having sides $(0 B_r)$ and $(0 H_c)$ with the demagnetization curve, as shown in Fig. 2.

Since the value of $(BH)_{max}$ is proportional to the maximum maintainable air gap energy per unit volume of a magnet, it constitutes a criterion of the magnetic quality of a permanent magnet material. It has been shown empirically that the quantity $(BH)_{max}$ is proportional to the product $B_r \times H_c$. Hence this product can also be used as a criterion of magnetic quality. It has also been shown that the

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coordinates B and H of the $(BH)_{\max}$ point are equal, respectively, to approximately 0.65 B_r and 0.65 H_c . Hence the determination of B_r and H_c for a material serves to determine its magnetic quality as a permanent magnet material, and also to determine the flux density at which magnets of the given material should be designed to work.

It has been shown also that the flux density of a fully magnetized bar magnet, designated B_{rm} , depends upon the length L and equivalent diameter, D , in the manner shown in Fig. 3. This curve holds for all permanent magnet materials, but applies strictly only to straight bars. The curve will also apply quite well to magnets of other shapes, however, unless the ends of the magnets are quite close together, or are brought effectively close together by iron pole pieces. In most cases the curve can be used as a check on the measured flux values of formed or cast magnets of various shapes when magnetized and tested as bare magnets. In these cases the actual flux values obtained should never be lower than predicted by the curve.

Testing of Magnet Materials and Magnets—Most manufacturers and large users of permanent magnet steels or alloys test the materials for magnetic quality by measuring B_r and H_c . The tests are made in some form of permeameter on straight bars of cast or rolled material, after proper heat treatment. Methods and equipment for making these tests are described in A.S.T.M. Standard Method of Testing A-34-33.

Most magnet users also make a flux test on the finished magnets. This test can be made most accurately with a search coil and a flux meter of the galvanometer type. Sufficient accuracy for commercial purposes and greater speed are obtained with flux meters of the direct current meter type in which the test magnet furnishes the field to deflect the moving coil of the meter.

Aging of Magnet Materials and Magnets—The magnetic properties of the permanent magnet steels are not stable with time. The residual induction and coercive force of most magnet steels begin to change spontaneously as soon as the steels are hardened and continue to change for an indefinite time. The rate of change is greatest immediately after hardening, and decreases rapidly so that in a few days the rate is slow. The rate and amount of change differ for different kinds of steel and are not uniform for any given kind of steel. The direction of the change is always for the residual induction to increase and the coercive force to decrease. Because of this instability, it is good practice for a user of magnet steel buying under specifications of magnetic properties to allow an aging period to elapse between the hardening and testing of test bars.

Because of their nature, and the kind of heat treatment employed, such aging phenomena are known to be much less pronounced in the precipitation hardened alloys and may be absent in some of them. An increase of coercive force with time has been observed in test bars of iron-nickel-cobalt-aluminum with no change in residual induction.

The state of magnetization of magnetized magnets made of a magnet steel is also subject to a peculiar instability. It is observed that magnets magnetized immediately or soon after hardening will spontaneously suffer a decrease in flux beginning immediately after magnetizing. The rate of loss of flux is greatest immediately after magnetization, and decreases rapidly with time, so that after several days the flux has reached an approximately stable value. If the magnet is remagnetized, the same phenomenon is repeated on a smaller scale. The phenomenon, however, is only temporary and disappears with a sufficient lapse of time after hardening.

This phenomenon is not found in the commonly used precipitation hardening alloys and is probably of negligible importance in all of them.

The loss of flux that occurs in magnets due to external demagnetizing influences is also commonly but improperly referred to as aging. External demagnetiz-

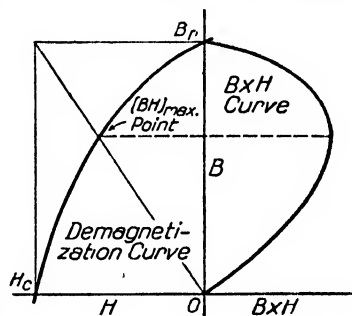


Fig. 2—Typical demagnetization curve of permanent magnet alloy.

ing influences include mechanical shock, adverse magnetic fields (this includes alternating current fields and the fields of other magnets) and heat. In general, if a magnet is weakened by any one of the above means, it will not be further weakened by a repetition of the same treatment and will suffer only a slight loss in flux from the application of any other treatment that would have weakened it originally by about the same amount. In the process inspection of magnets after hardening, some users follow the magnetizing operation by a partial demagnetization or "aging", before testing. The partial demagnetization in the inspection process is for the purpose of eliminating magnets that are improperly hardened or made of defective material and is not intended as a stabilizing treatment. If a stabilizing treatment is required, as for magnets to be used in measuring instruments, they may be stored for a long period of time, subjected to heat as by immersion in boiling water, or merely be partially demagnetized by an a.c. or d.c. field after final magnetization.

Methods of Magnetizing Magnets—The problem of magnetizing permanent magnets is becoming increasingly difficult with the advent of materials with coercive forces above 200 oersteds. The magnetizing field required fully to magnetize a magnet is several times the coercive force of the material, amounting in some cases to as much as 1500 ampere turns per centimeter. The magnets made of low coercive force steels and most magnets made of cobalt steel can be fully magnetized by means of large electromagnets. Precipitation hardened magnets of favorable shapes can also be magnetized by the same means, but magnets of intricate shapes made of cobalt steel or the precipitation hardening alloys can only be fully magnetized by winding heavy wire on each magnet and sending a heavy current through the wire by shorting the winding across a suitable source of heavy current. In this case, it is advisable to protect the current source and the winding by using a fuse in series. The fuse wire will melt and open the circuit before damage occurs to the current source or the magnet winding.

Magnet Steels—The types of magnet steel produced commercially in the United States are classified by their manufacturers as follows: Carbon-manganese, chromium, chromium-molybdenum, tungsten, and various grades of cobalt steel including cobalt-chromium and cobalt-tungsten. The chromium steels are made in grades ranging from nominal 1% chromium to 6% chromium, the tungsten steel ranges from 5-6% tungsten, and the cobalt steels contain from 3-36% cobalt with chromium from 2-10% and tungsten from 1-10%, and a fraction of 1% molybdenum in some cases. In some instances, the tungsten steels contain sufficient chromium to make them oil hardening. Otherwise, the tungsten steels, the 2% chromium steel, and the carbon manganese steels are water hardening and all the rest are oil hardening. It is noteworthy that the 1% chromium steel has the best magnetic properties when quenched in oil; but that water, some water solution, or a light oil are universally recommended for the 2% chromium steel. Data concerning the various types of magnet steel are shown in Table I. Only those types reported by various American manufacturers are included, and the data are summarized from information furnished by the manufacturers.

Manufacture of Magnet Steel—In general, the methods of melting, rolling, and fabricating magnet steels are similar to those used for tool steels of similar composition. Exceptions arise from the fact that mechanical properties are of secondary importance and practices which would be harmful to the magnetic properties must be avoided as much as possible. In particular, this means that the thermal history of the steel should be as brief as can be. Rolling or forging should be accomplished with a minimum amount of reheating and overheating should be avoided. Annealing should not be resorted to unless necessary for machining operations and the anneal should be as light as is consistent with machinability. Forming temperatures should be just high enough for proper working of the steel. It is rarely feasible to restore the magnetic properties of magnet steel which have been damaged by too prolonged heating or overheating.

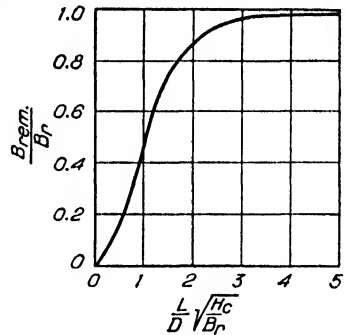


Fig. 3—Relation between magnetic properties and dimensions of straight bar magnets.

Melting and Rolling—Magnet steels are quite universally melted in electric furnaces, either arc or induction. One exception lies in the use of open hearth furnaces for melting carbon-manganese steel and the chromium steels of lower chromium content where larger tonnages are involved. In some cases ingots are cooled in lime, dry sand, or other material before rolling; but where possible it is preferable to break them down without cooling. This is done either by forging or rolling. Surface defects are generally removed by grinding. The rolling temperatures at start range from 1800-2100°F. and the finishing temperatures from 1300-1700°F., depending upon the critical temperature of the steel.

Hot Forming—In most cases, the shapes of permanent magnets are such as to require hot forming. This may be done satisfactorily at temperatures between 1400°F. and 1800°F. Higher temperatures are detrimental to the quality of the steel. A medium temperature is preferable and the heating and forming should be done as quickly as possible. Magnets are generally air cooled after forming. In some cases, magnets are hardened by quenching immediately following the forming operation, thus eliminating one heating operation. This practice requires better than ordinary control of the forming temperature.

Annealing—Too much emphasis cannot be laid upon the desirability of designing magnets so that they do not require annealing for machining operations. Where this is unavoidable, as light an anneal as possible should be used. Annealing always damages the magnetic properties of a magnet steel. Grades of steel which are air hardening must be annealed by the fabricator after the hot forming operation if machining is to be done on the formed magnets. Otherwise, annealing may be done at the mill if forming is not required or if the machining may be done before forming. Magnet steel should be heated to the annealing temperature quickly, held at temperature only long enough to be heated through and cooled just slowly enough in the furnace to avoid air hardening. In all cases, cooling from 1000°F. to room temperature may be done in the open air, since no air hardening will take place below 1000°F.

Hardening—The recommended hardening temperatures are specified in Table I. The optimum hardening temperature is that which gives the highest value of the product $B_r \times H_c$, except that some magnets are not designed for maximum efficiency and require higher values of B_r or H_c than are associated with the maximum value of the product $B_r \times H_c$. High values of B_r are best for long or slender magnets and high values of H_c for short thick magnets. Oil quenching results in higher values of H_c and lower values of B_r than water quenching. The latter results in a much greater amount of warping, cracking, and breakage. For this reason oil quenching steels are gradually replacing water quenching steels for most applications. Magnets should not be held at the hardening temperature longer than is necessary to heat them through.

Grinding—Great care must be exercised in grinding hardened magnets to avoid the production of grinding cracks which sometimes develop hours after the grinding operation. Wet grinding and light cuts are the best safeguard against grinding cracks.

Cast Magnets—Magnets of intricate shapes, chiefly made of cobalt steel, are frequently produced by casting. The properties of cast cobalt steel do not differ greatly from those of forged or rolled steel, although the coercive force is usually higher and the residual induction lower. The same annealing and hardening practices are recommended. The cast material is generally more brittle than the forged.

Miscellaneous—Reliable correlation of microstructure with magnetic properties has not been accomplished. In general, a fine, silky fracture is associated with good material. Decarburization should of course be avoided. Heating above 212°F. after hardening is detrimental to the magnetic properties. Actual damage begins to take place at from 300-400°F. Defective magnets may frequently be reclaimed by rehardening. There is, in general, no particular way of immersing magnets quenched in water which will minimize warpage or breakage. Tongs used in quenching magnets which must be formed to size just before the quench should be as light as possible to avoid cooling the magnets too much by contact with cold metal before the quench.

Precipitation Hardening Magnet Alloys—The range of possibilities for the design of permanent magnets has been greatly extended by the introduction of substantially carbon-free alloys of the precipitation hardening type. The magnetic

properties of any of the permanent magnet steels can be substantially duplicated by some of the possible carbon-free alloys and, in addition, materials having coercive forces greatly in excess of any of the magnet steels are commercially available, with still others in process of development. The alloys appearing to have the greatest commercial possibilities at the present time are an alloy of iron, cobalt, and molybdenum; and an alloy of iron, nickel, and aluminum; or iron, nickel, cobalt, and aluminum. The former has the advantage of slightly higher coercive force and residual induction than 36% cobalt steel, greater machinability, slightly lower density and lower cost. It has the disadvantage of greater brittleness. The latter alloys have coercive forces from 2-3 times those of 36% cobalt steel and residual inductions from $\frac{1}{2}$ - $\frac{1}{2}$ those of 36% cobalt steel. They have still lower density and cost, but they have the disadvantage of being neither forgeable nor machinable. Their use is therefore confined to magnet designs which can advantageously be cast.

The above alloys may, under proper conditions, be made to produce good magnets in the cast condition without further heat treatment, but in general, a high temperature solution heat treatment terminated, in some instances, by an oil quench, but generally by a rapid cool in an air blast and followed by a precipitation heat treatment is required for best and most uniform magnetic quality. The iron-cobalt-molybdenum alloy is machinable before and after the solution heat treatment, but not after the precipitation heat treatment.

It is possible to make magnets by the process of compressing and sintering the powders of the constituent metals. This process may also be applied to the production of magnets from the oxides of the constituent metals. The metallic oxide magnets have the peculiar property of being greatly improved by being magnetized at an elevated temperature. The improvement persists for subsequent remagnetizations at room temperature.

Properties of some of the carbon-free magnet alloys are given in Table II. Other alloys which have been reported include an iron-platinum alloy with coercive force of 1800 oersteds and a residual induction of 4000 gauss, an alloy of neodymium with iron having a coercive force of 4300 oersteds and a silver-iron alloy with a coercive force of 5000 oersteds. In these cases the residual induction is so low as to practically preclude the possibility of commercial usefulness.

Table I
Commercial Types of Magnet Steels

Type of Steel	Nominal Composition ^a , %						—Nominal— Magnetic Properties		Hard- ening Temp., °F.	Quench- ing Medium	Manu- facturer
	C	Mn	Cr	W	Co	Mo	B, gauss	H _c , oersteds			
C-Mn	0.60	0.80	....	....	....	....	10,000	43	1450	Water	1
Cr	0.60	0.40	0.90	....	....	....	10,000	50	1450	Oil	1, 2
	0.90	0.35	2.25	....	....	....	9,000	58	1500	Water, Oil	1, 2, 3, 4
	0.95	0.20-0.60	3.00-4.00	....	....	....	9,500	63	1525	Oil	1, 2, 3, 4, 5, 6
	1.00	0.35	6.00	....	....	....	9,000	72	1550	Oil	1, 3, 4, 6
Cr-Mo	1.00	0.35	4.00	....	....	0.35	9,000	65	1550	Oil	1, 4
W	0.70	0.30	0.20	5.50	....	....	10,000	65	1550	Water	1, 2, 3, 4, 5, 6
W-Cr	0.70	0.50	0.50	6.00	....	....	9,000	70	1525	Oil	1, 3, 6
Co	0.90	0.35	4.75	1.25	8.50	....	7,500	120	1650	Oil	3
	0.90	0.30-0.85	3.50-5.75	3.75-7.00	35.00-41.00	....	9,700	235	1700	Oil	2, 3, 4, 6
Co-Cr	0.95	0.30	9.00	....	16.00	1.30	8,000	180	^b	Air	3, 6
Co-W	0.85	0.50	2.00-5.00	8.75	17.00	....	9,000	165	1750	Oil	2, 3, 4, 6

^aSilicon limit usually 0.30 max., phosphorus and sulphur 0.03 max., nickel 0.50 max.

^bTriple heat treatment, 2100°F. cool in air, 1150°F. cool in air, 1850°F. cool in air.

^cValues for previously annealed materials usually 5-10% lower in H_c.

The above information is a composite from the following manufacturers:

1. Universal Steel Co.
2. Bethlehem Steel Co.
3. Halcomb Steel Co.
4. Carpenter Steel Co.
5. Ludlum Steel Co.
6. Simonds Saw and Steel Co.

Special compositions are also made to order but do not warrant listing in the table.

Table II
Precipitation Hardening Magnet Alloys*

Type of Alloy	Per Cent						—Nominal Magnetic Properties—	
	Ni	Al	Co	Ti	Mo	Fe	B, gauss	H _c oersteds
Fe-Ni-Al	24-30	9-13	....	....	....	Bal.	7,000-5,000	400- 600
Fe-Ni-Al-Co	24-30	9-13	5-10	....	....	Bal.	10,500-7,500	130- 650
Fe-Ni-Co-Ti	10-25	....	15-30	8-25	....	Bal.	7,600-6,300	780- 920
Fe-Co-Mo	....	....	12	....	16	72	12,000-8,500	50- 300
Oxide	Iron oxide, cobalt oxide						4,000	300-1,000

*The data so far reported on these materials vary rather widely both as to composition and properties. Standardization into a few recognized and useful types for commercial applications has not yet been accomplished and probably will not be until considerably more exploratory work has been done.

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The Creep of Metals and Alloys

By J. J. Kanter*

Definition of Creep—Creep is a continuing change in the deformation or deflection of a stressed member. With regard to metals and alloys, creep is generally associated with a time rate of deformation continuing under stress intensities well within the yield point, the proportional limit, or the apparent elastic limit for the temperature in question. The creep may be an effect of consequential magnitude at normal temperatures as well as at elevated temperatures, depending upon the material under consideration or the degree to which freedom from continuing deformation is sought.

Value of Creep—The first creep of metals studies of industrial importance were published by Dickenson¹ in 1922 on various steels and alloy structural members subjected to high temperatures in furnaces. His experiments served to demonstrate that commercial metallic materials, when used at elevated temperatures, underwent a steady rate of deformation under stresses well within the values allowed by good design practice and "safety factors" at that time. The creep of metals had been considered from the academic approach as early as 1910² and again³ in 1919.

As the temperatures of industrial processes steadily advanced and it was realized that troublesome deformations and even failures of equipment were being experienced at supposedly safe design stresses, critical inquiry into the behavior of metals at elevated temperatures was initiated. In 1924, realizing the industrial importance of these problems, the A.S.M.E. and the A.S.T.M. established a standing research committee for studying the effects of temperature upon metals which has sponsored two symposia,^{4,5} numerous reports, and technical papers.

At first, it was felt that practical stresses, below which creep either did not take place or was of inconsequential magnitude, could be determined for the various materials at elevated temperatures. Creep investigations made from this point of view were published by Lea⁶ in 1927 and French⁷ in 1926 which purported to show that proportional limits determined with sufficient delicacy might be regarded as "creep limits." Investigations published in 1928 by Kanter and Spring,⁸ in which

refinements of creep measurements had been made, showed that considerable rates of creep could be measured at stresses well below the lowest proportional limits determinable by the most delicate means available. At the higher temperatures, an increasing disparity between short time tensile test values and usable creep stress values was demonstrated, as illustrated in Fig. 1 by data for annealed cast carbon steel.⁹ It is now a commonly accepted fact that short time tensile test stress values are unreliable design criteria for elevated temperature use and that values determined by actual long time creep testing are to be preferred. Although working stresses based upon tensile strength "safety factors" are still authoritatively used as bases of design stress for the temperatures up to which creep is of inconsequential magnitude, the accepted basis of design for the higher temperatures is the selection of creep stress values. A summary of the status of creep studies in 1937 is to be found in the proceedings of the International Association for Testing Materials.⁹

Character of Creep—The bulk of available information on the character of creep has been gained from observations upon bars under constant tensile load and at

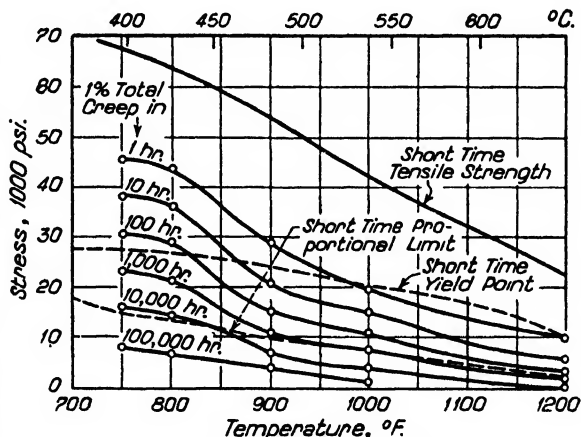


Fig. 1—Annealed cast carbon steel.

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constant temperature. Extensive studies have been made of the interrelation between creep strain, stress, and temperature by testing series of specimens under various combinations of load and temperature. A creep test is generally conducted for sufficient time to establish the character of the creep strain versus time curve at the particular constant load and temperature in question. Such a test, to be of significance, may require anywhere from a few days to several years. Tests of less than one thousand hours duration are not generally regarded as of much significance in reliably establishing creep rates.

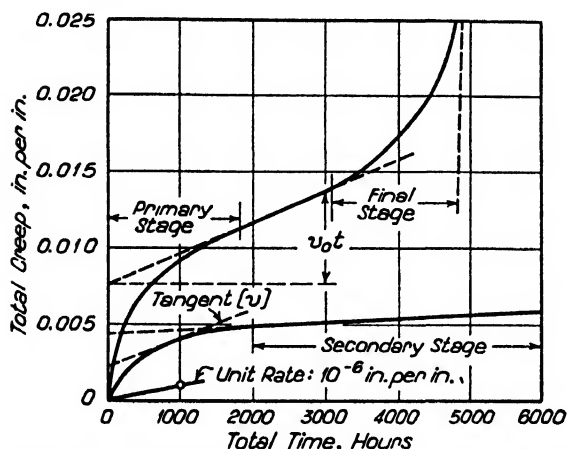


Fig. 2—Typical tensile creep curves obtained under different loadings for two alloy steels.

The second stage of creep is that strain occurring either at a constant rate or in asymptotic approach to a constant rate. The design of stressed members is generally based upon the rate of second stage creep strain. The useful life of a structure is for some purposes adjudged to be the time elapsed before the termination of the second stage. In Fig. 2 the upper curve shows second stage commencing at slightly less than 2,000 hours at a total creep of about one per cent and terminating slightly beyond 3,000 hours at a total creep of about 1.4%, where the rate of straining commences to increase. The lower curve shows no increase of rate up to 5,000 hours and tests are available in which the creep of metal specimens has continued in the second stage for several times this period. During the second stage of tensile creep the cross sectional area of the specimen remains sensibly unaltered, and thus the constant load creep rate is usually reported for practical purposes as a constant stress creep rate.

The third stage of creep is marked by an accelerating creep rate, leading to fracture. Although stress intensification and "necking" of the section contribute in the promotion of third stage creep, studies upon numerous materials have tended to show that this stage is generally reached at deformations much smaller than those sufficient to produce rapid creep to fracture through stress intensification only. Such evidence is held to be indicative of marked structural changes which strain, time, and temperature produce in metals and alloys.

Numerous mathematical discussions of the shapes of creep curves have appeared; noteworthy among these are papers by McVetty¹⁰ and Weaver.¹¹

Creep Stress—The practical aim of creep testing is generally the determination of stress intensities, at temperatures of interest, upon application of which the amount of deformation occurring is limited to tolerance values over a period of time comparable to the anticipated working life of the member to be designed. Creep stresses, as so defined, are generally based upon the rate of creep measured in the second stage and are justified as design values upon the assumption that deformation during the useful life of the equipment is largely confined to this approximately uniform rate of creep. For some materials and purposes of application the deformation accumulating in the first stage must be taken into account. Constant rate creep stress then becomes inapplicable and other creep stress values

In Fig. 2 are illustrated two typical tensile creep curves based upon results actually obtained under different loadings on two different alloy steels at high temperature. The strain designated as "total creep" is the net plastic deformation accumulated over and above the elastic strain immediately incident to the application of load. The initial creep upon a specimen not previously strained is invariably rapid, but as the straining progresses, the rate of creep decelerates until after an appreciable period a constant rate is approximated. This initial straining at a decreasing rate is frequently designated as the first stage of creep.

based upon the total deformation for the life period are desired. The bulk of available creep stress data, however, has been determined in terms of either the constant creep rate or tangents to the time deformation curve determined for some arbitrarily chosen time of test. An example of creep stress data for steel at elevated temperature is shown in Fig. 1, wherein a comparison with short time tensile strength, proportional limit, and yield point values is drawn.

Creep Testing Methods and Apparatus—The modifications of apparatus used in obtaining information upon metals vary widely in form and purpose. Although most study has been given creep under constant tensile load and temperature, numerous arrangements of apparatus have been devised for measurements in torsion, transverse bending, internal pressure, relaxation, variable loading, and variable temperature. Ample descriptions of the equipment used for tensile creep testing up to 1931 are given by Tapsell.¹² Since the publication of the Tapsell book, there have appeared a number of papers describing advances in tensile creep testing technique such as given in references 13, 14, 15, 16, 17, 18, 9, 19.

The A.S.T.M. has tentatively set up a creep testing code²⁰ for the guidance of investigators seeking to evaluate the tensile creep characteristics of metals. No attempt has been made in the code to prescribe a definite method of procedure or to specify apparatus, but rather to point out some of the possibilities, limitations, and pitfalls of creep testing. It is recognized that creep investigation is still largely a subject for metallurgical research and no hard and fast code rules can be set up which might not prove detrimental to the best interests of progressive research. Indeed, a newly proposed revision of the A.S.T.M. tentative method²¹ attempts to cover only such fundamental considerations as the amount of extension, the effect of temperature, the tensile stress, and the time. It is annotated in this new A.S.T.M. method that since the characteristics which render a material resistant to extension under the condition of test are not yet completely known, the only details of the procedure considered are those known to be important influences, and since others equally important may in the future be discovered, the recommended details of the method are largely advisory in nature.

Considerable latitude of practice among various investigators is found with regard to the choice of test specimens. The gage lengths in use generally vary from 2-20 in., while diameters vary from 0.252 to 0.505 in. Longer gage lengths are preferred for delicacy of measurement where minute creep rates are of interest. For metallurgical comparison purposes where the order of creep resistance is of primary concern, the 2 in. gage length is usually employed, as not only is the problem of specimen procurement simplified, but also easier test bar furnace and measurement technique may be employed. The 0.505 in. dia. specimen is generally preferred to the 0.252 in. because errors incurred due to scaling and consequent effect on cross section constitute less of an error.

Determination of the temperature of the specimen during the test is recognized by the A.S.T.M. code as the most important single measurement in connection with creep testing, because small variations in temperature may produce large changes in creep rate. Care must be taken to insure accurate temperature measurement over the gage length of the specimen throughout the test. Reliable temperature measurements must be made at sufficiently frequent intervals to insure an accurate determination of the average test temperature.

It should be here noted that a great part of the creep data to be found at present in the literature was obtained under conditions of test not acceptable under the proposed code. A confusion of creep values is to be found for certain compositions of steel. While much of the discrepancy is traceable to differences of heat treatment and other manufacturing variables, a goodly part of the disagreement must be attributed to lack of standardized technique and careful control of testing temperature.

Extension measurements are made through a number of devices, such as microscopes focussed on targets within the furnace or extension arms extending beyond the furnace actuating either optical levers or micrometer dial gages. Where total extensions are limited to the same order of magnitude as elastic extensions, it is important to have the elastic portion of the total extension accurately known.

The proposed revised A.S.T.M. code for creep testing, recognizing that much information pertinent to the intelligent evaluation of creep information has been lost through inadequate descriptions of materials used, recommends that essential information for identification of the materials tested be collected on a form which provides not only a most complete description of the material as to form, composi-

tion, and physical properties, but all manner of grain size information, manufacturing data, and auxiliary test information. The code also adopts a tabular arrangement for the reporting of the characteristics of the equipment used, intended to reflect the essential qualities of the measurements obtained.

Reliability of Creep Data—Considerable difficulty has been encountered by engineers seeking to use creep data, such difficulty being occasioned frequently by widely varying creep stress values for a given grade of material issuing from different authoritative sources. There has come about some reluctance on the part of creep investigators to attempt predictions of service behavior beyond the period of actual test until more knowledge is gained on how to measure reproducibly actual creep rates among the various laboratories.

Inconsistencies in creep data and testing are gradually being mastered, however, through cooperative efforts of various investigators and the Joint Research Committee (A.S.M.E.-A.S.T.M.) on Effect of Temperature on the Properties of Metals. A number of research projects are being carried forward through the donation of funds and work by industry and are directed toward systematically determining some of the perplexing difficulties encountered in the application of creep information.

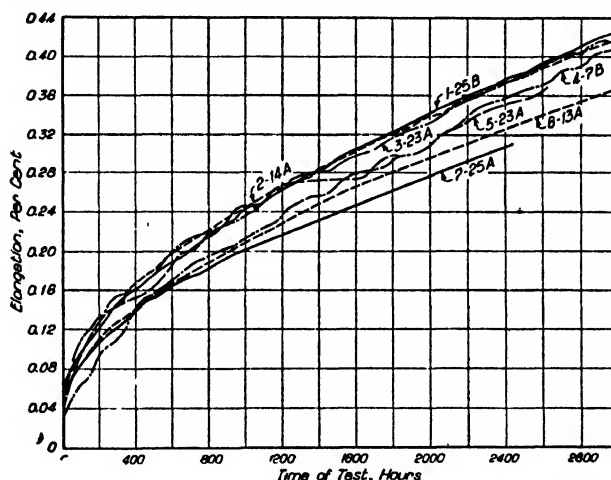


Fig. 3—Time elongation curves for a 0.35% carbon steel at 850°F. under stress of 7,500 psi. The curve numbers indicate the different laboratories.

A recent report¹¹ of this committee bears much of the fruit which has come of its efforts. In this report, an appendix prepared by C. L. Clark covers a series of creep tests on annealed 0.35% carbon steel at 850°F. under a stress of 7,500 psi. The bar steel used in the tests was prepared by one of the co-operating manufacturers with extreme precaution to insure uniformity of properties from test bar to test bar. Samples were distributed among various co-operating laboratories for test at 850°F. and 7,500 psi. stress. Laboratories reporting curves for this uniform material, measured in strict accordance with the provision of the Tentative A.S.T.M. Creep Test Method E22-35T were in excellent agreement as attested by the chart reproduced in Fig. 3. The steel used in this work, it is stated, was of at least as high a degree of uniformity as is possible to secure commercially under the present knowledge of melting practice, and the results obtained from the tests at 850°F. are in good agreement when the comparisons are based on creep strength. The conclusion is drawn from these results, however, that the creep rate and deformation characteristics are too sensitive an index of strength to permit exact duplication either in different laboratories or in duplicate tests in the same laboratory.

Factors in the Materials Tested Which May Influence Creep—In a carefully prepared preamble to the Joint A.S.M.E.-A.S.T.M. Committee's compilation¹² are summarized the factors which experience indicates must be considered as having a possible influence on the high temperature creep characteristics of steels. The factors so treated include melting process and practice, heat treatment, chemical composition, grain size, duration of test, number of tests, and various other influences.

In an appendix to the Joint Committee report,¹⁷ studies on the effects of manufacturing variables on the creep resistance of steels by H. C. Cross and J. G. Lowther emphatically demonstrate the effects which variation in austenite grain size may have upon creep rate. The results for the same 0.35% carbon steel for which creep curves are shown in Fig. 3 are summarized in Fig. 4, the spread between the rates designated for "coarse grain" and "fine grain" representing the decrease in creep rate of a steel effected through grain coarsening treatments. Similar conclusions were reached by Weaver²² with regard to the effect of what he describes as carbide grain size on the creep resistance of steels conforming to the S.A.E. 4330 at 840°F. General conclusions as to the effect of grain and carbide coarsening treatments whether affected by heat treatment through transformations or by recrystallization after cold working were reached by Kanter and Spring in 1928.^{5, 23} The profound effect which microstructure may have upon creep resistance is marked in studies upon alloy bolting steels where two heat treated structures of the same bar showing similar short time tensile test values may show widely variant creep strengths. In creep stress comparisons at 1000°F. the fine structure resulting from an oil quench and temper will sustain only one-quarter of the load permissible for

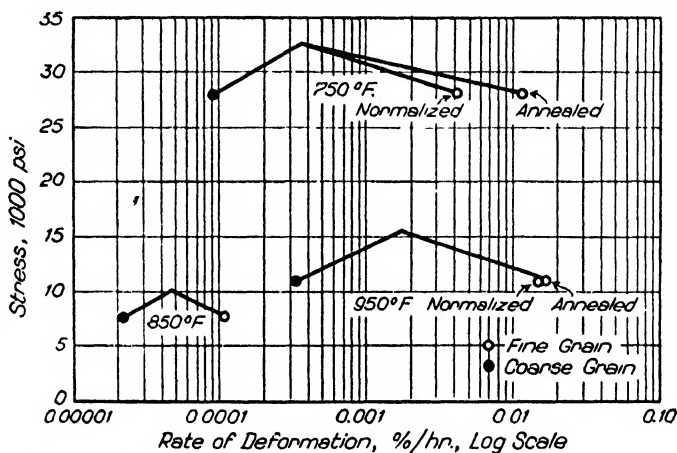


Fig. 4—Same 0.35% carbon steel as Fig. 3 with creep curves summarized.

the coarse structure obtained by a normalize and temper. A noteworthy study of the effect of heat treatment is to be found in a paper by Miller, Campbell, Aborn, and Wright.¹⁸

Source of Creep Data—The Joint A.S.M.E.-A.S.T.M. Research Committee on Effect of Temperature on the Properties of Metals undertook comprehensive compilation of creep data²⁴ from as many sources as could be reached. All laboratories known to be engaged in creep work, both in the United States and Europe, were canvassed for contributions to this compilation. The data were requested to be submitted to the committee compiled upon the A.S.T.M. creep test report form as adopted in the proposed revised code. Hitherto unpublished data were obtained for the compilation in this canvass. Additional valuable information was gained to supplement other data available in earlier literature. All information was critically co-ordinated with published data and assembled under the sponsorship of the Committee at the University of Michigan under the directorship of C. L. Clark. This book, over 900 pages in content, presents 430 sheets of test data, 270 graphs, and 73 tables covering wrought and cast carbon and alloy steels, including stainless steels and cast iron and nonferrous metals. (See also review by W. A. Baker.²⁵) All creep rate stress data are summarized upon log-log charts. Creep stress versus temperature charts showing comparison upon the basis of both composition and treatments are made for each class of material where data made available at the time of compilation permitted. This compilation has been published in its entirety by the A.S.T.M. and the A.S.M.E. A comprehensive tabulation of creep stress data is also to be found in a paper by Chadwick.²⁶ Other sources of data are listed in the appended references.

Acceptability Tests for High Temperature—Since it is impracticable to make a long time creep test on each heat of steel or heat treatment charge intended for service at high temperatures, considerable thought and study is being given to the development of some method of test which will assure that a particular lot of a given material has creep properties consistent with those dictated by the design requirement to which the material is being applied. The requirements for such a test are that it can be performed within 24 hr., that it will detect off-color heats of material and that the conditions of test, reproducibility of results, and correlation with creep data are such that mutual agreement can be reached between manufacturer and purchaser. A number of papers on the subject of the development of such tests have appeared by C. L. Clark, A. E. White, and others. An appendix of the Joint A.S.M.E.-A.S.T.M. Committee Report²⁷ summarizes the results of rapid time-to-fracture tests in comparison with long time creep tests on several steels. At this writing it is premature to draw conclusions on the general usefulness of such tests for specification purposes. The results are encouraging, however, and it probably will only be a matter of time until enough experience will be gained for various grades of materials to interpret brief time-to-rupture tests in the light of long time behavior. Noteworthy efforts to develop short "time-yield" stresses for acceptance purposes have been made by Hatfield²⁸ and some of the German investigators.²⁹

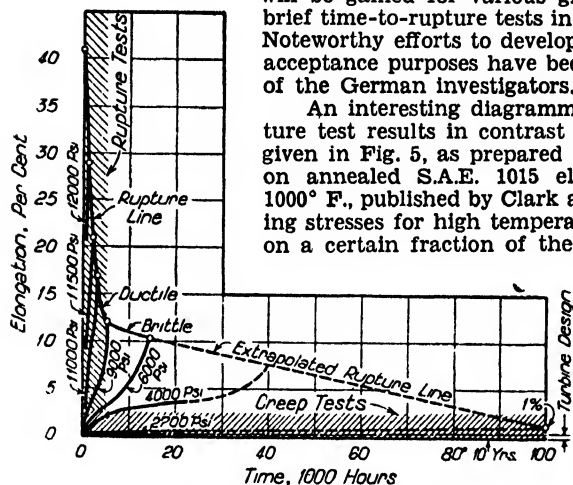


Fig. 5—Short rupture time test results in contrast to regular creep test. Annealed S.A.E. 1015 electric furnace steel, tested at 1000°F.

not usually show a stress for rupture less than would be chosen on a creep test basis unless a high creep rate is allowed. However, for the longer time intervals, the rupture strength gets to be considerably less than might be anticipated by some of the rules for selecting design stresses. The "life test" or "time-to-rupture" test can throw a good deal of light on the boundary region between strength tests and creep tests. Such tests make possible the determination, in certain instances, of which is the more important consideration, the possibility of rupture or excessive distortion. Since life tests and creep tests are distinctly different in character, representing quite different considerations, it is important to distinguish clearly the significance and value of each type of test. There appear but few cases, unfortunately, in which extended life tests have been carried out to deformations leading to rupture as were the tests depicted in Fig. 5.

Utilization of Creep Data—Space does not permit a digest of the mathematical and engineering theories and experiments bearing on the application of creep data. A rather extensive literature on this phase of the subject is to be found. A paper by Kanter,³⁰ prepared as a digest of the uses of creep results, contains numerous references to the work published up to 1936. Since 1936 a number of new papers on the applied mechanics of creep have appeared, some of which may be found in the Transactions of the A.S.M.E. such as papers by C. R. Soderberg, A. Nadai, J. Marin, and others dealing with applications of creep to compound stress systems, transverse bending, pressure tubes, flanges, relaxations of bolts, and various other special problems.

Allowable Working Stresses Based on Creep Data—The Boiler Code Committee of the A.S.M.E. proposes to revise allowable working stresses for ferrous materials used at elevated temperatures in accordance with the best available creep data. The creep data compilations of the Joint A.S.M.E.-A.S.T.M. Research Committee on Effect of Temperature on the Properties of Metals are used for this purpose. Allowable working stresses applying to steels at elevated temperature have been tentatively proposed³⁰ for inclusion in the A.S.M.E. Power Boiler Code. A diagram giving these working stresses at various temperatures is reproduced in Fig. 6 in which the steels are identified by their A.S.M.E. and A.S.T.M. specification numbers. The solid lines represent the various grades of carbon steel, with the exception of

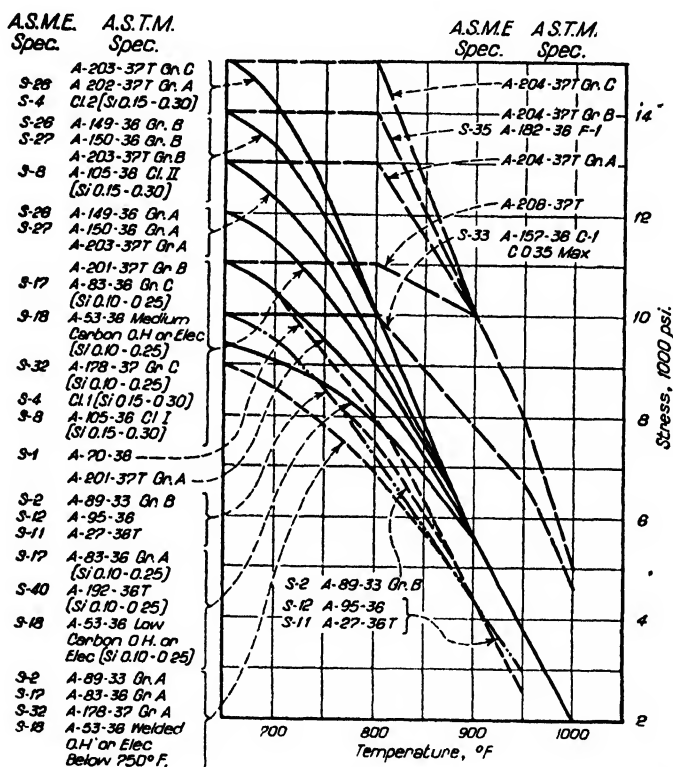


Fig. 6—Diagram giving working stresses for steels according to the A.S.M.E. and A.S.T.M. specifications.

A203-37T, which is 2½% nickel steel. The dotted lines represent various grades of carbon-molybdenum steel. The same allowable stress for any grade of carbon steel applies to all temperatures from 650°F. to -10°F. and is based upon one-fifth of the nominal tensile strength for forged and rolled material and one-seventh of the nominal tensile strength for cast materials. In the case of carbon-molybdenum steel grades these same rules apply to the temperature range 800°F. to -10°F. Above these temperatures (650°F. and 800°F.) the curves are based, conservatively upon creep stresses and the best experience. It will be noted that all the curves converge toward four common lines at the higher temperatures. The lower group of solid lines and the lower dotted line represent cast grades. These cast grades are rated more conservatively than corresponding forged or rolled compositions, but actually possess creep resistance equal to or greater than the wrought compositions. Allowable working stress ratings for elevated temperatures upon additional alloys, as well as extensions upon the proposals shown, are contemplated by the A.S.M.E. Boiler Code Committee after sufficient study of the creep data compilations has been made.

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Mass Influence in Heat Treatment

By E. J. Janitzky*

With an increase in the mass of steel of the same shape and composition, there is a corresponding change of physical properties when such pieces are quenched under identical conditions.¹ For example, if a series of round bars of different diameters of S.A.E. 1045 steel are quenched from the same temperature by the same procedure into the same quenching medium, the physical properties of the quenched bars will vary in a regular manner dependent on the diameters of the rounds. This difference will also be evident, although different in value, after the usual tempering operation. This difference in physical properties is due to the rate of decomposition of austenite, which has been shown by Bain² to be very slow at the beginning of the transformation (100% austenite), increasing to a maximum at about 50% transformation and again becoming slow as the reaction nears completion (Fig. 1). Alloys such as nickel³, chromium⁴, and manganese⁵ increase the hardenability in the same size and shape of piece, that is, makes the steel deep hardening, and they effect the rate of decomposition of austenite.

The hardenability as measured by a hardness test depends not only on the diameter of the section which is heat treated but also on the depth within the piece at which the hardness is measured if the section is large enough so that it has not hardened completely, that is, to the center. This would also be true of physical properties such as tensile strength, yield point, elongation and reduction of area if they were to be determined at different depths within the piece. Characteristic hardenability curves⁶ are shown in Fig. 2 in which the Rockwell "C" hardness of water quenched rounds of various diameters are plotted against diameter of the section. Fig. 2 shows a plain carbon steel, S.A.E. 1045, at the left, and a deep hardening alloy steel, S.A.E. 6140 at the right. In $\frac{1}{2}$ in. round the S.A.E. 6140 has hardened completely and in 1 in. round nearly so. In $\frac{1}{2}$ and 1 in. rounds of

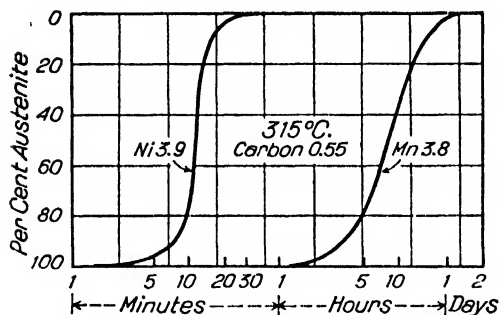


Fig. 1—Direct comparison of reaction time in a nickel and a manganese steel. Both steels contained about 0.55% carbon and 3.8% alloy. (Bain²)

section is increased and, after reaching a maximum, decreases again as the mass becomes so great that the steel is practically inert to heat treatment.

Tensile strength and elastic limit will decrease with increase in the diameter of the section while elongation and reduction of area will increase. In bars smaller in diameter than one which will just harden completely, there is relatively little change in physical properties with size in commercial quenching operations. In the sizes which fall somewhat short of complete hardening, the change in physical properties with size is relatively rapid but diminishes as the size is increased until the mass becomes so great that the steel is practically inert to heat treatment. Alloying with chromium, nickel, or manganese counteracts this inertness while combinations of chromium, nickel, or manganese with vanadium, molybdenum, or tungsten may or may not have deep hardening potentialities, depending on the composition, grain size and heating temperature.

Suppose that a series of rounds of S.A.E. 1045 and a similar series of rounds of an alloy steel, such as S.A.E. 2340, have been quenched under identical conditions.

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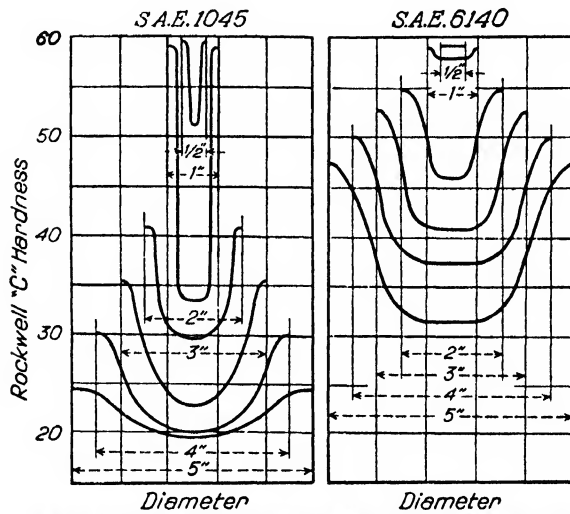


Fig. 2—Hardenability curves in which the Rockwell hardness is plotted against the diameter of the sections. (Grossman.⁴)

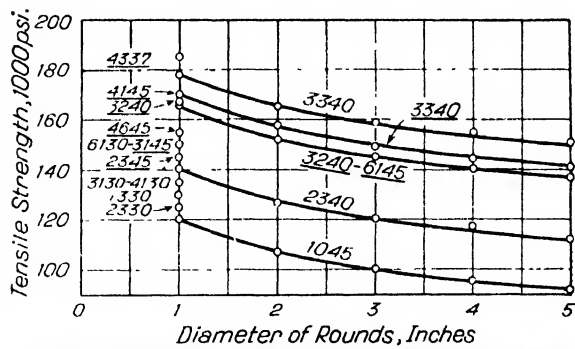


Fig. 3—Relationship between tensile strength and diameter of sections for several steels.

A series of physical properties changing with increasing size will be obtained for each steel. However the physical properties of the S.A.E. 2340 series will be different in value for identical diameter than in the S.A.E. 1045 series due to the presence of nickel in the S.A.E. 2340 steel. Similar effect will be obtained by the use of any of the alloys mentioned above although the value of the change in hardenability will depend on the alloying element and its percentage in the steel together with the carbon content of the steel. These alloys affect not only the hardenability in quenching but also cause the steel to resist tempering more than do plain carbon steels.

The relationship between tensile strength and diameter of section for S.A.E. 1045 and several common alloy steels is shown in Fig. 3. These steels were normalized, then quenched from appropriate temperatures into oil or water as indicated and tempered at 1000°F. The oil quenched specimens are underscored in Fig. 3. The tensile tests were taken from midway between center and surface of the quenched and tempered rounds except for the 1 in. rounds in which the tests were taken from the center. It is evident that the decrement in tensile strength in each steel bears a regular relationship to the increase in diameter of the section. The following relationship was observed: As the diameter of the section increases in arithmetic progression, the tensile strength decreases in hyperbolic order according to the following equation:

$$P_2 = P_1 \left(\frac{d_1}{d_2} \right)^n$$

in which P_1 = the tensile strength corresponding to the diameter d_1 and
 P_2 = the tensile strength corresponding to the diameter d_2 .
 n = exponent (different for each curve).

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The Marked Similarity in Tensile Properties of Several Heat Treated S.A.E. Steels

By E. J. Janitzky* and M. Baeyertz†

The effect of increasing tempering temperature on the tensile properties of heat treated S.A.E. structural steels is usually represented by a series of charts, each chart applying to one carbon content within one S.A.E. type. With the growth of our knowledge of the tensile properties of plain carbon and alloy steels, however, it has become evident that the tensile properties of one might almost be substituted for those of another *provided* that the appropriate heat treatment for each has been applied. This has seemed to justify the following attempt to assemble these numerous tensile property charts into a few charts which show *general relationships* applicable to the S.A.E. structural steels as a group.

The charts presented have been assembled from data on test specimens of S.A.E. structural steels which have been heat treated in a definite manner. Such heat treatment is necessary in order to obtain interchangeability of the tempered steels on the basis of tensile properties. The requisite heat treatment may be any commercial quenching operation *provided* that the steel and the section be such that the test specimen used will *harden throughout when quenched*. The nature of the quenching is immaterial provided that the cooling rate is such that the resulting structure is martensite, which in many instances undoubtedly contains more or less retained austenite. Thus a given section of an oil hardening steel which will harden throughout if quenched in oil will also harden throughout if quenched in water. On the other hand, a given section of a water hardening steel which will harden throughout if quenched in water *may not harden throughout if quenched in oil*. This is caused by the greater hardenability of oil hardening steels as compared to water hardening steels. It is not customary, because of the high stresses developed, to harden thoroughly as large sections in water as in oil; hence oil hardening steels will harden throughout by oil quenching in much larger sections than are feasible by water quenching the so-called water hardening steels. In fact this is the property which has led the engineer to group steels in water hardening and oil hardening grades. If test bars of the S.A.E. structural steels are hardened throughout and are then tempered to the same tensile strength, they will have the same yield

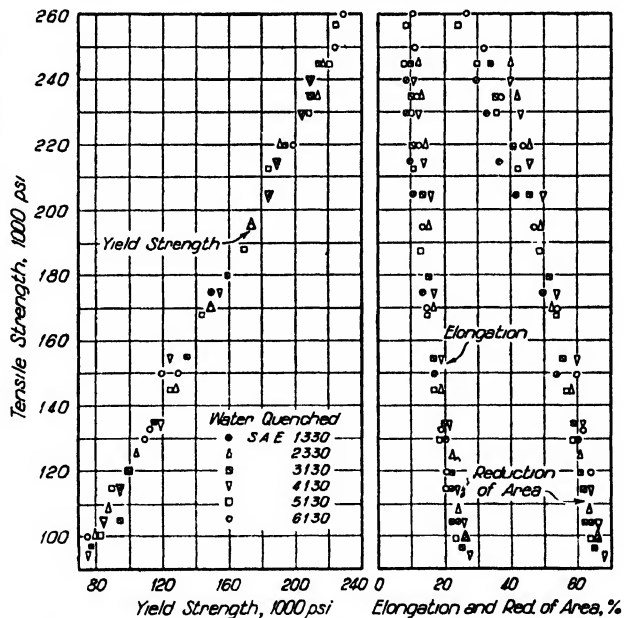


Fig. 1—Data on the tensile properties of several S.A.E. water hardening steels. One inch round bars were normalized, quenched in water, according to S.A.E. recommendations, then tempered at various temperatures from 400-1300°F.

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Prepared for the Subcommittee on Alloy Elements, the membership of which was as follows: Jerome Strauss, Chairman; H. B. Knowlton, Walter Crafts, J. W. Sands, E. C. Bain, A. J. Herzog, L. L. Ferrall, E. J. Janitzky, and C. H. Herty, Jr.

strength, the same elongation, and somewhat the same reduction of area *provided* that the tensile strength is below about 200,000 psi. This is illustrated by Fig. 1, 2 and 3. Moreover, if tempered to the same tensile strength, they will have the same Brinell hardness as shown by Fig. 4.

Fig. 1 shows the assembled data on the tensile properties of various S.A.E. water hardening grades. One inch round bars were normalized, quenched in water, according to S.A.E. recommendations, and then tempered at a series of tempering temperatures from 400-1300°F. The tensile properties were determined on standard 2 in. x .500 in. ± .005 in. dia. tensile test pieces machined from these bars. Without regard to the tempering temperature required to produce any given tensile strength, the tensile strength of each test piece has been plotted (Fig. 1) against the yield strength, elongation, and reduction of area obtained on the same test piece. Fig 1 shows that there is little difference between the various S.A.E. grades with regard to the other tensile properties which accompany a given tensile strength *provided* that a tensile strength of 200,000 psi. is not exceeded. It should be noted, however, that the *tempering temperature* required to produce any given tensile strength may be different for the different S.A.E. grades.

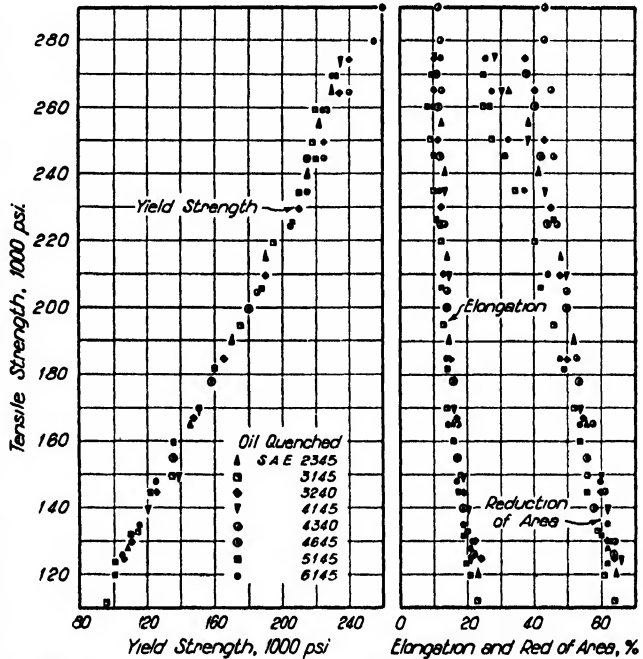


Fig. 2—Data on the tensile properties of several S.A.E. oil hardening steels. One inch round bars were normalized, quenched in oil, according to S.A.E. recommendations, then tempered at various temperatures from 400-1300°F.

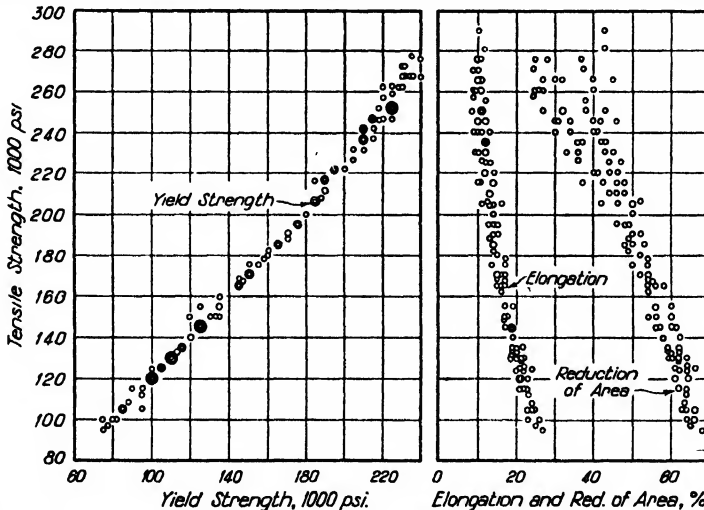


Fig. 3—Data from Fig. 1 and 2 on water and oil hardening steels plotted on a single diagram.

Above a tensile strength of about 200,000 psi., steels tempered to the same tensile strength have the same yield strength and elongation, but the reduction of area becomes an independently variable property depending on the individual steel. It is our belief that this variation is the result of retention of a variable amount of *austenite on quenching*, and the structural features which accompany the decomposition of such retained austenite at low tempering temperatures.

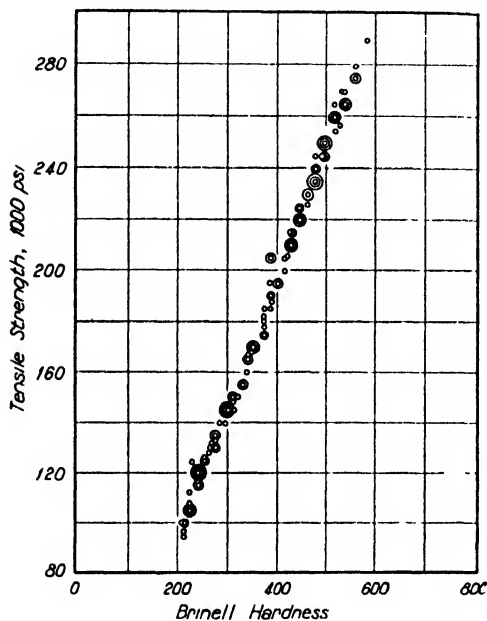


Fig. 4—Brinell hardness plotted against tensile strength for the steels shown in Fig. 1 and 2.

ening and oil hardening S.A.E. steels on the basis of tensile properties, provided that the steels are quenched in such a manner that each steel will harden throughout.

Fig. 4 shows the Brinell hardness number plotted against the tensile strength for the same steels as shown in Fig. 3. It is apparent that water hardening and oil hardening steels, if hardened throughout and then tempered to the same tensile strength, are interchangeable on the basis of Brinell hardness.

One point remains for discussion, namely, the change in tensile strength with increase in tempering temperature. This relationship is shown in Fig. 5 for the various water hardening and oil hardening grades, using the same experimental data as in Fig. 1 and 2. Many of the points in Fig. 5 would have been superimposed if they had been plotted exactly on the 100°F. steps of tempering temperature which were actually used in testing. The designation for the various steels have therefore been grouped around each tempering temperature while their exact position in relation to the tensile strength axis has been retained. Under the experimental conditions imposed, the tempering temperature required to produce a given tensile strength is a function both of the alloy content and the carbon con-

Fig. 2 shows a compilation of similar data for various oil hardening grades quenched in oil in one inch rounds, according to S.A.E. recommendations, and then tempered. Again there is little difference in tensile properties between the various grades, provided that the test bars are tempered to the same tensile strength and provided that a tensile strength of 200,000 psi. is not exceeded.

Fig. 3 comprises all the data on water hardening steels in Fig. 1 and on oil hardening steels in Fig. 2, plotted on a single diagram. Because of the larger number of experimental points, the designations representing the individual S.A.E. grades have been abandoned and circles have been used to indicate all experimental points. Fig. 3 shows the interchangeability of quenched and tempered water hard-

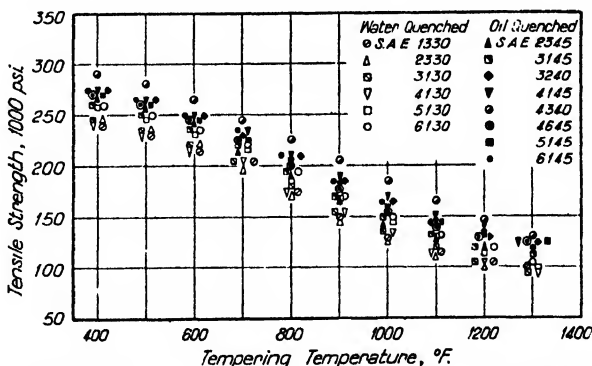


Fig. 5—Change in tensile strength with increase in tempering temperature for water and oil hardening steels. The specimens were held at temperature for 30 minutes.

tent of each steel. This relationship must therefore be determined experimentally.

An example of the use of the figures just presented may not be amiss. Suppose, for instance, one desires to obtain a given tensile strength using one of these S.A.E. steels as hardened throughout and tempered in one inch round section. It follows from Fig. 3 and 4 that the accompanying yield strength, elongation, reduction of area and Brinell hardness number will also be fixed within narrow limits provided that a tensile strength of 200,000 psi. is not exceeded. Thus if a tensile strength of 170,000 psi. is desired, then according to Fig. 1, 2 and 3 the yield strength will be approximately 150,000 psi., the elongation will be approximately 16%, the reduction of area will be approximately 54%, and according to Fig. 4 the Brinell hardness number will be approximately 350, no matter which of these S.A.E. steels is used *provided* only that the steel shall be *hardened throughout* prior to tempering. The tempering temperature which is required to obtain this tensile strength and accompanying properties, however, *will vary with the steel used* according to Fig. 5. For example, using S.A.E. 2330 the tempering temperature required to obtain a tensile strength of 170,000 psi. is 800°F., while S.A.E. 6130 must be tempered at 900°F. and S.A.E. 4145 at 1000°F. in order to obtain a tensile strength of 170,000 psi.

It will be evident from the foregoing discussion that the S.A.E. structural steels are substantially equivalent on the basis of mechanical properties as determined by the tensile test under the following conditions:

1. If the sections are so chosen that the test pieces of each steel are *hardened throughout on quenching*.
2. If the test pieces are *tempered to the same tensile strength*, irrespective of the tempering temperature necessary to produce that tensile strength.
3. If a tensile strength of 200,000 psi. is *not exceeded*. Under the above conditions of quenching, the tempering temperature required to obtain a given tensile strength depends both on the alloy and the carbon content of the steel and must be determined experimentally

The Alloying Elements in Steel

By Edgar C. Bain*

The metal iron, exceeded in abundance by only three other elements in the earth's crust, has been reduced from its ores largely by the agency of carbon, even from its earliest utilization; for a high yield of iron carbon is employed plentifully. Therefore the products of the reduction carry carbon—together with small amounts of such other associated elements as carry through the process or are introduced from the fuel and reducing agent and even the operation of oxidizing away the undesired portion of the carbon in steel making may permit some of the impurities to remain. Thus, practically, iron is found in commerce not as a high purity metal, but chiefly as a metal with a moderate degree of "impurity." These unsought accompanying elements and such amounts of correctives as are used to facilitate steel making are not generally regarded as forming an alloy steel. Of all the elements, it is this same inexpensive carbon which appears to have the most pronounced and generally speaking, beneficial effect, upon the physical properties of the element iron.

Iron, then, not so much in spite of as because of its impurities, forms, with increasing carbon (say 0.03-4.0%) a series of alloys, first steels and finally cast iron, which provide an array of materials unparalleled in variety and applicability. But such limitations as do exist in this amazing series of metals may be greatly extended by the intentional incorporation of some proportion of other of the elements, principally, though not wholly, the metallic ones. These alloying elements as advisedly added to iron and steel enhance the desired properties in the resulting alloy steels (and iron), and below are some of the specific objectives toward which the alloy additions in steel are directed.

- A. Enhancement of Mechanical Properties.
 - 1. Increase in strength of steel as manufactured.
 - 2. Increase in toughness or plasticity in steel with any minimum hardness or strength.
 - 3. Increase of allowable maximum section which may be quench-hardened to desired properties.
 - 4. Decrease in quench-hardening capacity.
 - 5. Increase in rate of hardening with cold work.
 - 6. Decrease in plasticity at given hardness in the interest of machinability.
 - 7. Increase in abrasion resistance or cutting capacity.
 - 8. Decrease in warping and cracking in development of desired hardness.
 - 9. Improvement of physical properties at either high or low temperatures.
- B. Enhancement of Magnetic Properties.
 - 1. Increase in initial permeability and maximum induction.
 - 2. Decrease in coercive force, hysteresis and watt loss (magnetically "soft" iron).
 - 3. Increase in coercive force and remanence (permanent magnets).
 - 4. Decrease of all magnetic responses.
- C. Enhancement of Chemical Inertness.
 - 1. Decrease of rusting in moist environment.
 - 2. Decrease of attack at elevated temperature.
 - 3. Decrease of special attack by chemical reagents.

The foregoing examples are engineering desiderata and contain no clue to the actual physical-metallurgical effects of the alloying elements which ultimately bring about these useful engineering advances. A study of the articles on the individual steels immediately following this section will amply show that no element, merely by its benign presence alone, commands a degree of hardness, softness, toughness, brittleness or compatible combinations without regard to its effect upon the structure of the resulting alloy steel. For this reason, the articles on the individual alloys and their respective alloy steels have much to do with constitution diagrams; with the microstructural phases, which are favored by one element, opposed by another, or even eliminated. It may well be stressed that the rates of the reactions occurring in the heating and cooling, be it a mere cooling from the rolls or a quench and temper, are of just as great importance as the reactions themselves and that the most powerful means of controlling these rates lies in alloying elements. Accordingly particular enlightenment may be secured by a comparison of the equilibrium diagrams with the constitutional diagrams showing the constitution of the various alloy steels after specific representative treatments.

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Although the following chapters show that the tremendously important individual physical characteristics of alloy steels are not simply conferred by the added elements, there are nevertheless only a limited number of things these elements may do, only a few ways in which they may exert their great influence upon the steel; and accordingly the philosophy of alloy steels is probably not in fact complex, for all its ultimate variety. This chapter sets forth this philosophy for the medium carbon, medium alloy steels which constitute the major tonnage.

While a comparatively small proportion of an alloying element usually suffices to modify appreciably the properties of steel in some manner, some of them make their presence manifest at far lower concentration than that required for others. When relatively very large amounts of the alloying elements are present the characteristic behaviors of the carbon steels are generally obliterated and such high alloy steels will not be treated in detail here, however important they may be; their behaviors and properties are so individually characteristic, and so far removed from those of carbon steel as to warrant the special treatment they receive in other chapters. In this category will be found Hadfield's high manganese steel, Invar (iron-nickel), and the austenitic stainless steel family, as well as the low carbon, high chromium alloy steels (chromium in excess of about 15%) which are not subject to the allotropic change characteristic of carbon and medium alloy steels.

Under the chapter "The Iron-Carbon Alloys" it will be seen that annealed carbon steel consists of two essential substances: (1) Soft, alpha iron (ferrite), and (2) hard, iron carbide (cementite), both of which may carry dissolved elements. In addition there are usually some nonmetallic particles which (fortunately) prevent too great grain growth in the steel, and which (unfortunately) occasionally assume microscopic dimensions which are regarded as undesirably large. When suitably heated, such steels undergo the well known transformation in which the ferrite and the carbide mutually react to form a single, new solid solution,—austenite. Upon cooling, the austenite reverts to ferrite and carbide, but with a range of characteristics which exceeds in variety that known in any other metallic system. Even in carbon steel, carrying roughly half of one per cent carbon, the hardness may be so great as to enable it to scratch glass or so low as to permit easy deformation,—a range due almost wholly to structure, that is, to the fineness and mode of the carbon (carbide) distribution. How then do the alloying elements superimpose their vast effects upon this control of structure? Clearly the first requisite is a knowledge of the distribution of the elements in the phases of the steel.

Distribution and Effects in Annealed Steel—In the annealed steels under discussion here, the alloying element has clearly a limited choice as to its location, that is, as to how it can distribute itself. It may be:

1. Dissolved in the ferrite:
Al, Si, Ni, Cu, P, and Co (Zr) very largely; Cu not in excess of some ¼%; Mn, Cr partially; largely so with low carbon content; nearly all elements in customary proportion in low carbon steel except S, O and high Cu.
2. Combined (if carbon is sufficient) in the cementite or special carbide phase:
Ti, V, Nb, Ta, W, Mo largely; Mn, Cr in part, depending upon carbon content.
3. Combined with other elements to form special compounds and nonmetallics:
Al in Al_2O_3 or aluminum silicate; Si in SiO_2 and silicates, Zr in ZrO_2 , V in oxide, et cetera; Cr in $Cr_2O_3 \cdot M_2O_3$ in high chromium steel; Ti, Zr, V, and high Al in nitrides, S in sulphides; possibly Si and Ni, Al and Ni, Cr and Si in corresponding intermetallic compounds when present in large amount in low carbon steel.
4. Dispersed in elemental form (rare):
Cu in excess of some 0.75%;
Pb under some conditions.

It is essential that it be realized that these categories are nonexclusive; in principle each element may be in three (or more) phases as indeed clearly manganese not infrequently is. The elements listed under each phase are merely those which are particularly prone by nature to concentrate there. Generally speaking, the most insoluble (inactive) state forms preferentially until one or the other elements involved approaches depletion after which the element concentrates in the remaining possible locations. Thus titanium will form carbide, nitride or oxide until it is largely exhausted or the carbon, nitrogen or oxygen nears depletion whereafter the remaining titanium will be dissolved in ferrite. Aluminum will combine with most of the oxygen and nitrogen; if some then remains it will be dissolved in ferrite since it is not found in the carbide phase. Very little nickel

is found either in inclusions or in the carbide. Silicon combines with much of the oxygen and the remainder is largely dissolved in ferrite for it is not a carbide forming element in steel. Obviously the location of the carbide forming elements depends upon the carbon content, and the deoxidizing elements will be found in ferrite only when present in relative excess of the oxygen. To repeat, trends only are shown above; the actual distribution depends upon the amount of the element present relative to the amount of other elements, on the basis of the partition coefficients of the phases. Nevertheless the distribution pattern is highly characteristic for each element.

Metallographic Effects of the Elements According to Distribution. (Annealed Steel)—In Ferrite—All of the elements as dissolved in ferrite increase its hardness and strength and, in differing degree, most of them simultaneously reduce its ductility. This mode of strengthening iron is mild by comparison with that of an effective dispersion of hard particles, but it does not take as great a toll in plasticity. Nickel, for example, is exceedingly sparing in its impairment of ductility. The effect of elements in solid solution in the ferrite matrix is best studied in a series of nearly carbon free alloys, although it may also be evaluated in higher carbon alloys if the same carbide volume and distribution is maintained in all compositions. Other effects, described beyond, may be superimposed upon the solid solution effect.

It is probably not generally realized how little of the extra strength of some alloy steels is contributed through the solid solution effect; yet high strength structural steels to be welded without special precautions must derive a large share of their strength improvement from this effect.

In Cementite or Carbide Phase—In one respect the different varieties of metallic carbides found in annealed alloy steel are similar. They appear to increase the total hardness and strength similarly for equal volumes and size of particles; all are relatively so hard that this would be expected, even though some are more voluminous than others for the same carbon content and may resist abrasion or function in cutting tools somewhat differently. The several elements, however, which appear in the carbide phase (be it the cementite or a special crystal form) have a vast disparity in diffusion rate, and therefore in the amount of coalescence occurring under like conditions. No element, so far as is known, joins with carbon (and iron) in forming a carbide with greater diffusivity than pure cementite, Fe_3C . This circumstance is suggestively consistent with the "weakness" of the pure compound Fe_3C which is always more or less undecided whether to form or dissociate.

In Nonmetallic Compounds—In the annealed alloy steels the nonmetallic compounds exert comparatively little influence upon properties except to contribute slightly to hardness or if in excessive amount in the form of threads, to decreased transverse ductility. It is in part this same adverse effect which results in improved machinability. The important role of the nonmetallic particles is discussed in the next paragraphs.

Distribution of Elements at Elevated Temperature—When the alloy steels are heated, as in hot working or for hardening, into the temperature range for complete or maximum austenite formation much the same changes occur as in carbon steel. Certain elements raise this requisite minimum temperature range, others lower it, that is, for the substantial disappearance of ferrite and solution of some or all of the carbide. In low carbon steels with sufficient proportions of the elements more soluble in ferrite than in austenite some ferrite may persist at all temperatures but these are borderline alloys approaching those not within the present scope. At suitable austenite forming temperatures the alloying elements are then found:

1. Dissolved in the gamma iron solid solution:
Nearly all elements seemingly dissolve in at least small proportion, and most of them in large amount, except as partially combined to form strong carbide compounds in higher carbon steels or as nonmetallic compounds.
2. Combined with carbon to form persistently insoluble carbides:
Ti, Ta, Nb, and V, largely with high or even medium carbon; Mo, W partially, depending upon carbon content.
3. Combined with other elements to form special compounds or nonmetallics:
Al in Al_2O_3 or aluminum silicate,
Zr in ZrO_2 , V in oxide,
Si in SiO_2 in silicates (somewhat dissolved),
Cr in Cr_2O_3 , MnO , in high chromium steel,
S in special sulphides,
Ti, Al and Zr in nitrides (somewhat dissolved).

Much of the previous discussion of the distribution of the elements in annealed steel applies here in principle, except that the carbide phases are vastly more soluble in austenite than in ferrite, and some nonmetallic inclusions are dissolved. So far as is known no element increases the solubility of carbon beyond the maximum 1.7% in pure iron-carbon alloys. All the strong carbide forming elements greatly reduce the maximum solubility of the carbide phase. It is not at all uncommon to quench such alloy steels with considerable carbide still undissolved.

Metallographic Effects of the Elements According to Distribution at Elevated Temperature (Above or Near Upper Critical)—*In Austenite*—When the annealed alloy steel is suitably heated the elements previously in the ferrite are at once incorporated into the austenite as well as all such elements as were combined in such carbide as may dissolve. In the case of nickel, copper, and manganese steels and certain chromium steels the temperature for complete austenite formation is lowered below that of pure iron-carbon alloys; the other elements raise the temperature. In alloy steels wherein all carbide disappears there is metallographically little difference from the austenite of carbon steel except as to rate of formation, homogeneity and grain size. Certain elements are said to coarsen the austenite grain, but this impression almost certainly results from the customary higher heating temperature employed or to prior effects having to do with attendant change in the nonmetallic content. When much fine carbide, either by intentional suppression of heating temperature or time, or by virtue of its low solubility, remains undissolved the austenite grain size remains fine, or, at least, does not increase much from the initial magnitude. The principal effect of the alloying elements dissolved in austenite has to do with the transformation rate upon cooling, an important subject which is discussed in subsequent paragraphs.

In the Carbide Phase—When the alloying elements are to be found in considerable portion in the carbide phase the resulting carbide is less soluble at any certain temperature than that of the cementite of plain carbon steel. Thus at heat treating temperature such undissolved carbide robs the austenite of both carbon and alloying element. Such undissolved carbide particles may serve a good purpose, as in high speed steel. The effect of undissolved carbide may be great in that little grain growth in the austenite beyond its initial fine grain size occurs while any considerable number of fine special carbide particles remain. It is probably due to this circumstance that the vanadium, tungsten, and molybdenum steels are generally fine grained; the carbide is usually not wholly dissolved—when it is, coarsening may begin at once. At exceedingly high temperature the grain may coarsen somewhat whether or not some carbide remains, as in high speed steel, for the last carbide particles to dissolve are the large, and therefore ineffective ones. Other important effects are in turn brought about by austenitic grain size and these are treated in the following section.

In Nonmetallic Inclusions—Some nonmetallic inclusions increase in solubility when the metal is heated well into the temperature range for the austenitic condition. With solubility raised and diffusivity inevitably increasing it is not surprising that some coalescence of inclusions takes place in austenite. Other inclusions, notably the aluminum compounds, coalesce exceedingly slowly; indeed, aluminum itself diffuses slowly, which may be somewhat the same thing in essence.

The most important function of inclusions, particularly the fine ones, is that of restricting grain growth. The example usually cited is that of thoria particles in tungsten and the effect is spoken of as "grain growth obstruction." This designation may be descriptive but scarcely aids in suggesting a mechanism* for the preservation of fine grains at higher temperature when the solid solution carries a dispersion of foreign particles.

Dispersed particles raise the temperature of grain growth but usually bring about a greater abrupt coarsening when coarsening does occur. For this reason, nonmetallic inclusions are of importance in steel and the significant point is that exceedingly small amounts of inclusion forming elements, notably aluminum in the presence of oxygen, or perhaps nitrogen, may alter the characteristics of a steel profoundly by virtue of grain growth effects. Nonmetallic particles may be more effective than insoluble carbide particles in the restraint of grain growth.

*Perhaps the particles, by providing copious nucleation during recrystallization upon heating, merely contrive to produce a grain system wherein all the fine grains are of substantially the same small size and consequently there is no family sufficiently smaller than the others as to merge with them and thus cause grain growth.

Alloying Elements in Hardening—Thus far, it may appear, no very profound changes in physical characteristics have been traced to the alloying elements although the valuable solid solution type of hardening of ferrite and certain grain growth effects of special carbides and inclusions have been noted. The considerable solubility of many of the elements in austenite and the effect upon austenite grain size of others have been pointed out, however, and herein lies, by all odds, the greatest of the effects of alloying elements.

Alloys Dissolved in Austenite—It has been explained in many recent publications how austenite, upon cooling, does not immediately transform when it reaches a temperature at which ferrite and carbide (not austenite) are stable, but that it delays during a period of so-called nucleation. Accordingly it is possible to utilize this period of lag to cool the piece to a temperature as low as 200°F. or lower, before transformation begins and when this is accomplished the steel is hardened. The product is then not lamellar pearlite (with or without proeutectoid constituents) as would in carbon steel have formed near the critical temperature; instead, hard martensite is formed. The interior of a piece of steel cools more slowly than the surface layers and often, when a piece is quenched and superficially hardened, it transforms near the center at temperatures (A_r') producing the softer ferrite carbide aggregate. The larger the section quenched the slower all zones cool in any medium so the hardened exterior is relatively thinner in large sections. The cooling rate, necessary to prevent the A_r' transformation and enforce the low temperature transformation, at A_r' , to martensite is called the "critical cooling rate." The temperature range which identifies this critical rate obviously lies between the critical temperature and that at which the A_r' reaction is most rapid, that is, for carbon steels from 1330°F. to around 930-1020°F. One may say then that hardenability is a function of maximum transformation rate in the A_r' range and accordingly, of the critical cooling rate in the active temperature range.

So far as known, all elements, except cobalt, when dissolved in austenite (of any certain grain size) decrease the maximum A_r' transformation rate, decrease the critical cooling rate and therefore increase hardenability. How cobalt is an exception is not known but it appears to confer a specific mobility to the crystal resulting in high transformation rate. The elements vary in this respect as to effectiveness. Nickel, aluminum, silicon, chromium, and manganese (somewhat in order of increasing effectiveness) are moderate in effect, while curiously enough, when actually dissolved, the carbide forming elements are exceedingly effective, so that the amount actually dissolved need be only relatively small to accomplish a considerable increase in hardenability. Grossmann has communicated that an increase of silicon from 0.16-0.32% resulted in a change of depth of hardening in a 1% in. round of 0.60% carbon steel from $\frac{1}{4}$ - $\frac{1}{2}$ in. An increase of 1% manganese in a tool steel may permit oil hardening instead of water quenching. The rate of transformation may be so decreased by alloying elements that heavy billets as cooled in the air will not transform except at temperatures so low as to form the harder, acicular structure. In a somewhat different category are the large additions of nickel, manganese or combinations with chromium which prevent all transformation even at low temperature, so that the alloy is persistently austenitic.*

This same hardenability effect operates to alter the lamellar, pearlitic structures which result from cooling at subcritical rates. A low transformation rate permits the steel to cool to a lower temperature before the transformation sets in and as a result a pearlite of finer lamellar spacing, and therefore of higher hardness, is produced. This feature is taken advantage of in such high strength steels as are not specially heat treated but used as cooled from rolling or normalizing temperature. In such steels, generally hypoeutectoid, the proportion of free ferrite is likewise lessened with increased hardenability for any carbon content.

It should be emphasized that the effect of dissolved elements to increase hardenability is the most important basis for their use.

Alloys in Undissolved Carbide—It has been shown that many carbide-forming alloys greatly reduce the solubility (and incidentally the rate of solution, sometimes confused therewith) of the carbide phase in austenite, and undissolved carbide may remain at heating temperature. This means that the carbon content of the austenite

*Hardenability is a function of transformation velocity in the A_r' temperature region. In principle it is not involved at all with the retention of untransformed austenite after quenching; even carbon steels retain some austenite along with the martensite and some alloying elements, for example, manganese, cause retention of austenite to a greater extent than other additions for the same hardenability.

is correspondingly lower than that of the steel as a whole and if the carbon content is high, the austenite is likewise leaner in alloying element (such as Ti, V, Mo, W or Cr) than the over-all analysis indicates. This lack of solution of the carbon is reflected in the softer martensite produced, for martensitic hardness is influenced much more by carbon than by any other element. However, this effect is generally less important than that of undissolved carbides upon grain size.

A change in austenitic grain size from about a No. 8 to about a No. 2, A.S.T.M. standard, may slow up the transformation rate some 6-10 fold, or as a rough guide an increase of two A.S.T.M. numbers often about doubles the transformation rate for any given composition. In a carbon tool steel, for example, halving the transformation rate (decrease of two A.S.T.M. numbers) may increase the depth of hardening (based upon 55 Rockwell C) from about $\frac{1}{8}$ in. to about $\frac{1}{4}$ in. In a steel (1 in. round) of greater hardenability the same increase in grain size may, for example, raise the hardness, $\frac{1}{8}$ in. from the center, from 50 Rockwell C to 63-64. The direct evaluation of hardenability by determining transformation rates is involved with experimental complexities. The simple, practical hardenability test of penetration of martensitic hardening to measured depths in one suitably sized bar is more satisfactory and, moreover, amenable to interpretation for another size. General "laws" relating these various manifestations of the same fundamental factor are currently presented by Grossmann, Azimow and Urban.* An approximation of the depth of hardening for any size bar can be made by plotting the ratio of hardened depth to radius against the reciprocal of the diameter squared, and since this is in part nearly a straight line function, only two points are required. This method is currently being presented by Queneau and Mayo.*

To sum up, carbide particles left undissolved, or especially when they are insoluble by nature at the heating temperature, restrain grain growth and to this extent limit the hardenability of whatever austenitic composition carries them. Thus a fine grained, alloy bearing steel may have the same hardenability as a coarse grained carbon steel; the deep hardening effect of the alloy being offset by the shallow hardening effect of restricted grain size with an overall gain in toughness.

Alloys in Nonmetallic Particles—In previous sections it was pointed out how the nonmetallic particles restrict grain growth as do carbide particles and often with greater efficacy. Seemingly the alumina bearing inclusions are particularly effective in this way and accordingly yield steels of low hardenability for a given composition in alloying elements.

Alloying elements then influence hardenability in any form they may take:

1. Increase hardenability (except cobalt) as dissolved in austenite.
2. Decrease hardenability (by restricting grain growth) as incorporated in insoluble carbide particles or nonmetallic inclusions.

The effect of grain size control upon hardenability alone would scarcely be of consequence if it were not for the superior toughness of the heat treated transformation products from fine grained austenite. The energy absorbed in the breaking of two quenched and tempered bars, identical except for prior austenitic grain size, may have a ratio of 5-1 if the grain size of the tougher bar is 4 or 5 grain size numbers finer than the other. The tendency toward quenching cracks, warpage and grinding cracks is greatly reduced for any steel by a finer austenitic grain size; the superior properties are apparent in the freshly quenched martensitic condition and in the moderately tempered products as well. There is evidence that the benefits of fine grain are in large part due to internal stress, for microscopic cracks are hardly found in martensite from fine grained austenite but become increasingly prominent in coarser grained specimens.

An element which is partly dissolved and partly combined as persistent carbide may thus at once contribute deep hardenability and toughness through grain growth restriction.

Alloying Elements in Tempering—In freshly quenched steel the alloying elements are largely in the martensite; some remain in undissolved carbide and inclusions. These latter play small part in tempering. It is taken as established that the real function of tempering depends upon the formation and coalescence of carbide particles. Because of the preponderance and ubiquity of iron there can be little doubt that the first carbide particles to form (and start growth) are predominantly

*Hardenability of Alloy Steels, A.S.M., 1939.

of iron carbide, since minimum diffusion is thereby involved. Later the special carbide elements assert themselves and in some cases the Fe_3C particles are no longer exceedingly small when this occurs. Often considerable softening has occurred before the carbon migrates to form a fine dispersion of special carbide which then retards or halts the softening or causes a "secondary" hardness.

Elements which remain in the ferrite solid solution during tempering exert the solid solution effect, a strengthening with little loss in plasticity. The special carbide particles are of great importance in that their coalescence is slow, and hence the hardened alloy steel resists softening at higher temperature than does carbon steel. This makes possible high creep strength. Furthermore the stresses in the ferrite matrix (inherited from the severely stressed martensite) are doubtless greatly reduced by the higher tempering temperature possible in alloy steels (carrying carbide forming elements) when any certain degree of final hardness is sought. This alone will explain much of the superior toughness of alloy steels, though the fineness of austenitic grain is probably still more potent in enhancing plasticity and toughness in quenched and moderately tempered steel.

During tempering the alloying elements influence the steel in that they (1) dissolve in the ferrite matrix to improve strength and to resist ferrite recrystallization; and (2) form a persistently fine dispersion of more slowly coalescing special carbide which, for any hardness, allows higher tempering temperature and accompanying alleviation of internal stress in the matrix.

Nonmetallic dispersions so far as is known have practically no effect upon tempering or carbide coalescence. Very large inclusions of course are undesirable.

It is important to bear in mind that prior austenitic grain size alone has no significant effect upon the rate at which martensitic steel softens during tempering. This is due to the fact that grain size does not alter carbon diffusivity, true both for ferrite and austenite. Thus the preservation of fine grains by the use of small amounts of aluminum to form an aluminum oxide type of dispersion is found experimentally to have no effect upon the rate of carbide agglomeration at any certain temperature. When austenitic grain growth is restricted as only one manifestation of a definite alloying effect (as with vanadium) the softening during tempering is, of course, modified. In both instances, however, transformation rate, and hence transformation temperature at any particular cooling rate is changed and this difference in temperature produces a different degree of carbon diffusion.

The alloying elements serve to improve the properties of heat treated steel in still another way, that is, by bringing about acicular structures having mechanical properties superior to those of lamellar structures but still without involving first a full martensitic hardening.

Some alloy steels have certain special transformation rate characteristics by virtue of which a moderately slow continuous cooling results in transformation at a somewhat elevated temperature to a slowly formed, acicular structure,* softer than martensite, having a spheroidal carbide dispersion. Its superior properties, with or without tempering, are probably due to lower internal stress somewhat as in the direct transformation product produced in carbon and low alloy steels by rapid quenching to intermediate temperature and maintenance thereof for deliberate transformation.

Equilibria in Alloy Steels—While it cannot be denied that a knowledge of the influence exerted by the several alloying elements upon hardenability and grain size and thus upon the final resultant strength, and toughness of the heat treated steel is of primary importance, some interest attaches to the constitution of alloys of each element alone with iron, and a great deal more to the iron-carbon alloy ternary equilibrium and constitutional diagrams.

The principal constitutional effects of the various elements upon iron relate to melting point, α (δ) \longleftrightarrow γ (A_1) and γ \longleftrightarrow α (A_1) transformations and the magnetic change point A_2 . Depending upon whether or not the elements form iron-rich compounds and whether they restrict or widen the temperature range of the γ form of iron, they fall into a system of four categories. It must be stated, however, that the influence of an element as reflected

*The names troostite-martensite, self tempering martensite, pseudo-martensite, cubic martensite and bainite have been used to describe this structure. The last is the name applied, however, to the similar, direct transformation product of "Austempering" also mentioned in the next sentence.

in its binary alloys with iron has little to do with its important effect upon steels other than those of very low carbon content. Attempts to classify alloy steels on the basis of the binary diagrams have been almost useless. For example, it was thus erroneously assumed that nickel and manganese, which "stabilize" austenite would be the most effective retarders of transformation of austenite in medium alloy steel, whereas some of the elements which stabilize ferrite, and form carbide, are actually more effective.

With respect, however, to the ternary equilibrium diagrams, considerable needed information is here provided. The effect of the element upon the temperature necessary to produce austenite, the shifting of the eutectoid composition, the solubility of the carbide, and the compositions exhibiting special carbide, are all essential items of information in gaining acquaintance with the alloying elements in steel. There are other diagrams, based not upon equilibrium at all, but showing instead just which constituents and aggregates are actually established after specified treatments, that are even more informative. Some of these are available. It is hoped that many more will be worked out from time to time. What the equilibrium diagram cannot show is the rate of change from one condition to another with a change in temperature (for example, hardenability); it can tell nothing of the retardation of these changes due to low diffusion rates; finally, the ternary diagrams based upon pure alloys are not necessarily applicable to commercial materials which carry elements employed for steel making facility. Notwithstanding these shortcomings the philosophy of alloys in steel cannot be built up without a knowledge of the trends, and the constituency toward which the alloys move as the tendencies more and more assert themselves.

Conclusions—In the foregoing paragraphs, it has been shown that alloying elements in steel may exert only a certain few basic influences upon fundamental behavior and properties. An element may exert the usual solid solution effect toward strengthening the ferrite, or when dissolved in austenite profoundly enhance the hardenability of the steel. When the alloying element is combined with carbon (and some iron) the resulting special carbide may restrict austenite grain growth at heat treating temperature and, as formed after quenching, during tempering, it may, with benefit, necessitate and permit higher heating temperature for any certain degree of softening. As combined to form dispersed nonmetallic inclusions it may restrict grain growth or in other larger particles improve machinability. These fundamental influences serve to impart valuable engineering properties.

It might be anticipated, then, that many alloy steels intended to be heat treated are similar. Indeed when suitably heat treated to develop similar austenitic grain size and a similar hardness, the mechanical properties at ordinary temperature are almost indistinguishable as between many different analyses. The same cannot, of course, be said of chemical properties such as corrosion resistance. It is sometimes forgotten that, within its rather narrow limits of cross section, carbon steel may be so treated as to secure room temperature properties approaching those of many low and medium alloy steels. This limitation of size is, however, a serious one, and in overcoming this feature the addition of alloying elements contributes one of its foremost benefits. The effects upon fundamental mechanical properties of the alloying elements are all, so far as is known, gradual and very largely predictable in nature however critical they may seem for any particular application. The precise degree of an alloy effect will have to be determined experimentally although approximate interpolation of properties for intermediate proportions is not impossible. There are few, if any, instances wherein abrupt physical changes actually accompany slight changes in proportion of added elements and even less probable are any unexpected sharp maxima of good properties at certain ratios or proportions among the elements. There is a persistent belief, perhaps valid, that the use of two elements having similar effects instead of one somehow brings about more than the expected sum of effects. Since few alloying effects are measured in dimensions or quantities which are in nature linear or additive, this impression may be erroneous.

Table I sets forth some of the basic trends of the elements in terms of metallographic effects. These effects may be translated into property trends in light of the concepts set forth heretofore. The table refers to a fairly broad range—medium to high—of carbon content, but not to the very low carbons, and some allowance is made for the amount of element customarily employed in low and medium alloy steels.

Table I
Trends of Influence of the Alloying Elements

	As Dissolved in Ferrite: Strength	As Dissolved in Austenite: Hardenability	As Undissolved Carbide in Aus- tenite: Fine- Grain, Toughness	As Dispersed Car- bide in Tempering: High Temp. Strength (and Toughness)	As Fine Dispersion of Nonmetallic: Fine Grain, Toughness
Al	Mild	Mild	None	None	Very strong
Cr	Mild	Moderate	Strong	Moderate	Slight
Co	Strong	Negative	None	None	None
Cb	?	?	Strong	Strong	None
Cu	Mild	Mild	None	None	None
Mn	Strong	Moderate	Mild	Mild	Slight
Mo	Moderate	Strong	Strong	Strong	None
Ni	Mild	Mild	None	None	None
P	Strong	Mild	None	None	None
Si	Moderate	Moderate	None	None	Moderate
Ta	Moderate?	Strong?	Strong	Strong	None
Ti	?	Strong?	Very strong	Little*?	Moderate?
W	Moderate	Strong	Strong	Strong	None
V	?	Very strong	Very strong	Very strong	Moderate?
Zr	?	?	None?	None?	Strong?

*As a result of very slight solubility.

Chromium Steels

By Walter Crafts*

Description and Sources of Chromium—Pure chromium is a soft, fairly ductile metal with a blue-white metallic luster but the commercial forms which contain small amounts of impurities are relatively hard and brittle. Physical constants are given on page 78. It has limited use as a pure metal except as addition to non-ferrous alloys.

Chromium was first reduced to the metallic condition by Vauquelin in 1797 and was added to steel by Berthier in 1821, who immediately recognized the resulting greater hardness, magnetism, and resistance to acid. In 1822 Faraday and Stodart recognized the superior oxidation resistance. It is of interest that these properties are basically those for which chromium is used today, although their significance and useful development were not realized for almost a century.

Starting with the addition of chromium to structural steel by Baur in 1865, the commercial use of relatively small amounts of chromium in tool, ordnance, and engineering steels has increased continually. The production of low carbon ferrochromium led the way to high chromium-low carbon steels of the stainless type. Brearley developed stainless cutlery steel containing 11-14% chromium in 1913, and with the oxidation resistant chromium irons of Becket and the austenitic chromium-nickel steels of Strauss and Maurer, the application of stable surface steels containing large amounts of chromium developed in enormous strides. Resistance of these steels to food, chemical and atmospheric attack has permitted technological, mechanical, and stylistic changes whose effects on our civilization may be as yet but dimly realized.

The only industrially important chromium mineral is chromite of the nominal composition $\text{FeO} \cdot \text{Cr}_2\text{O}_3$. The ore usually occurs in massive form but frequently is found as grains in a serpentine matrix. The luster of chromite is submetallic to metallic; the density is 4.32-4.57 and the hardness is 5.5 on the Mohs scale. The ore is widely distributed although the most important sources are Turkey and Rhodesia. Although a fairly large amount of chromite was mined in the United States during the World War, the bulk of the normal requirements is supplied by other countries. For metallurgical purposes the ore should be of a massive structure, contain at least 48% Cr_2O_3 , and have a chromium to iron ratio of at least 3 to 1.

Ferrochromium containing 60 to 72% chromium is used for adding chromium to steel and is made in several grades with carbon contents ranging from 0.05 to 9%. The ore is reduced in an electric furnace, with carbon for the high carbon grades and with silicon for the low carbon alloys, to produce ferrochromium containing 60-72% chromium. A description of ferrochromium and its introduction into steel is given in the section on "Metals and Ferroalloys Used in the Manufacture of Steel".

Structural Influence of Chromium in Steel and Cast Iron—On account of its utility in promoting hardness and toughness, and also wear, oxidation and corrosion resistance, chromium is commonly used in steel and cast iron in amounts ranging from a fraction of a percent to 35%. As indicated by the diagrams described in the articles on the Constitution of Iron-Chromium Alloys and Iron-Chromium-Carbon Alloys, a wide range of structural characteristics is developed, which produce marked changes in physical properties. Many extra-equilibrium structures of importance are readily obtainable by virtue of the characteristically slow rate of

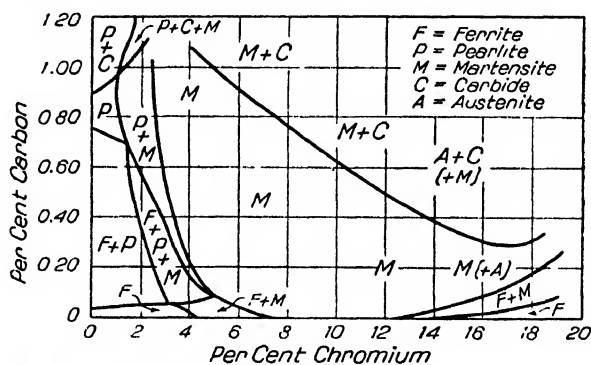


Fig. 1—Constitutional diagram for chromium steels. Normalized in $\frac{1}{2}$ in. sq. sections.

*Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

there is also a tendency for austenite to be retained. The effect of mass is illustrated by the differences between Fig. 1 and 2. Specimens from which Fig. 2 was determined were bars approximately 1 in. in dia. which were heated to approximately 1750°F. and air cooled. Significant differences between the two diagrams are restricted only to the relatively high carbon contents. General features that are common to both diagrams are the lowering of the carbon content of the eutectoid composition, development of martensitic structures over a wide range of carbon and chromium, and the range of ferritic high chromium steels that result from restriction of the austenite field.

The broad structural classifications with their approximate chromium contents are as follows: 1. Pearlitic chromium steels, -0-2%; 2. Martensitic chromium steels, -2-17%; 3. Ferritic chromium steels, -17-35%; and 4. Austenitic chromium steels, -10-30%.

These groupings are only approximate and the composition limits may be shifted by heat treatment and minor alloy additions. They are, however, sufficiently typical to serve as a basis for illustrating the many effects of chromium in improving carbon steel and conferring special properties.

Pearlitic Chromium Steel—Although chromium is usually added to pearlitic steels to increase the hardness, ductility or toughness, amounts of less than 0.50% chromium are widely used in carbon steel and the more simple alloy steels to increase moderately the hardenability. Chromium tends to reduce segregation, has a slight grain refining capacity, and has the property of making steel "normal" in the McQuaid-Ehn carburizing test. The latter property is of particular value in preserving uniform hardening capacity in steels made fine grained with aluminum.

When over 0.50% chromium is used, the greater hardenability, decreased mass effect, and toughening become more effective. In low carbon high strength structural steels chromium is typically a toughening rather than a hardening addition. It increases the impact resistance at subzero temperatures and has a specific effect

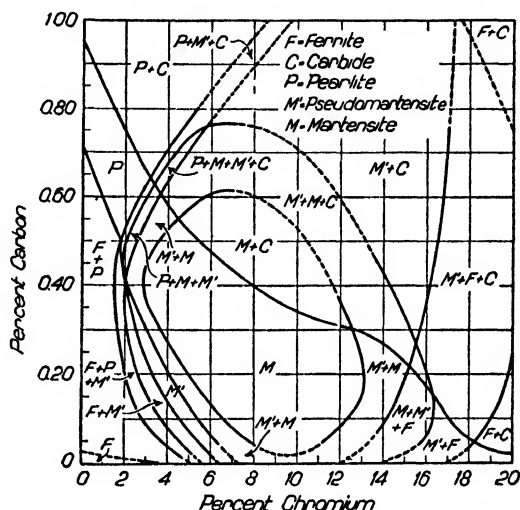


Fig. 2—Constitutional diagram of chromium steels containing 0.50% manganese normalized in 1 in. dia. bars.

on the brittleness introduced by high phosphorus contents as shown in Fig. 3. The corrosion resistance conferred by phosphorus and copper is enhanced by chromium, although the tendency of chromium to impart corrosion resistance is barely appreciable at 1% chromium unless some special condition, such as abrasion, is involved.

Chromium carburizing steels are used in applications requiring a high degree of surface hardness and wear resistance. S.A.E. 5120 is used for general purposes, and higher chromium steels are used for severe duty where higher core strengths are necessary. Chromium is also used in complex carburizing steels containing vanadium, molybdenum, nickel, and manganese.

Heat treated 1% chromium engineering steels of the S.A.E. 5100 types develop appreciable freedom from mass effect at a relatively low cost and are of specific value for wear and fatigue resistance at moderately high strengths in structural parts, springs, and gears. Modified 1% chromium steels of the S.A.E. 3100, 4100 and 6100 types also have wide application for similar purposes. Higher chromium contents are less widely used, but find application in articles of larger section. The 2% chromium-vanadium steel used in pressure vessels for ammonia and alcohol synthesis is especially resistant to hydrogen embrittlement. Some application of steels containing about 2% chromium is also made, usually in conjunction with other alloys, in moderately severe elevated temperature service.

Chromium has long been used in tool steels in order to obtain extreme hardness, as in drills, chisels, and files. Such steels are deep hardening and where toughness is desirable are made with a fine grain size. Chromium is also used in low tungsten chisel, die and finishing steels to improve the hardening characteristics. Superior wear resistance, which seems to be a specific property of chromium carbide, makes 1-2% chromium of considerable value in tool steels for rolls, shearing dies, and certain types of cutting tools. Ball bearing steel is the preeminent application of this kind and contains about 1% carbon and 1.5% chromium.

Somewhat larger amounts of chromium are used in hot working die steels to increase the hardening capacity and wear resistance. Both tungsten and molybdenum types of high speed steel contain about 4% chromium, which controls to a major degree the hardenability of the steel and is an essential factor in developing adequate toughness and hardness. It also facilitates heat treatment, assists in the formation of well distributed small carbide particles and improves the retention of red hardness.

Steels containing approximately 1% carbon and from 1-5% chromium are the most widely used of the permanent magnet steels. Where practical, the steels are hardened in water to develop the best magnetic properties, although oil hardening is the usual treatment. Although the best properties are obtained at about 3% chromium, the economical balance has been found to lie at about 2% chromium.

Chromium both alone and in conjunction with other alloys is used in cast iron to improve the strength, wear resistance, and thermal stability. In the range of 0.5%, chromium increases the strength by reduction in size of the flake graphite and the retention of more pearlite. The matrix in the areas of eutectic graphite is made pearlitic so that the sources of excessive wear are largely eliminated. The breakdown in structure after prolonged heating is minimized by chromium. Above about 0.75%, chromium produces primary carbides in gray iron that make machining difficult, and higher amounts produce a wear resistant white iron. Irons containing

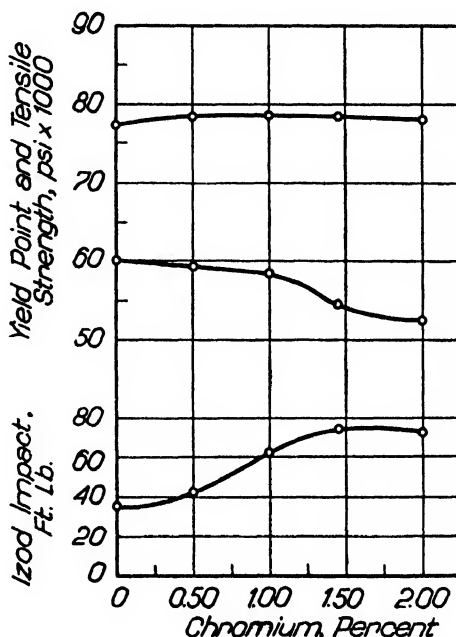


Fig. 3—Effect of chromium on normalized steel containing 0.10% C, 0.35% Mn, 0.09% P, and 0.80% Si.

1-2% chromium are resistant to wear and moderately severe high temperature service and are used for applications such as grinding balls, grate bars, and incinerator parts.

Martensitic Chromium Steels—The martensitic range of chromium steels containing 2-17% chromium is used for almost as broad a variety of applications as the pearlitic steels, although the utility depends in greater degree on the surface stability conferred by chromium. With higher chromium, the effect of mass, and resistance to wear, corrosion, and oxidation, increases.

Steel containing 0.20-0.40% carbon and 2-4% chromium is pseudomartensitic in the air cooled condition and has unusually high ductility and toughness at a tensile strength of about 180,000 psi. Railroad rails of this composition, as well as similar steels of higher carbon content, are extremely wear resistant. The high ductility at high strength is readily developed in steel castings. Steels of this chromium content, usually in conjunction with molybdenum, tungsten, silicon, aluminum, and vanadium, are used for moderately high temperature service.

More severe service requires a higher chromium content, and in oil refining stills steels of 4-6% chromium are most widely used although some steels of higher chromium content are used to combat more extreme conditions. The 4-6% chromium steel contains a carbon content of less than 0.20%. Molybdenum or tungsten is usually added to increase the creep strength at elevated temperatures, and columbium or titanium is used to stabilize the carbides and prevent air hardening. Chromium confers some strength at elevated temperatures, but its primary effect is to reduce oxidation and the corrosive effect of sour oils. The effect of chromium on oxidation resistance is illustrated in Fig. 4. Steels of the silicon-chromium type with higher carbon and higher silicon, in some cases with secondary alloys, are used for valves in internal combustion engines in which the high strength and resistance to corrosion by the combustion gases make an effective combination.

At about 12% chromium the resistance to corrosion by oxidizing media becomes much higher, and steels containing 12-18% chromium are widely used for cutlery. The low carbon grade is cold rolled to develop hardness suitable for cheaper knives. This steel also has an extremely high order of mechanical properties after heat treatment, and is used for turbine blades and valve trim. The steels containing 13% chromium with 0.30-0.40% carbon, and 16-18% chromium with 0.60-0.80% carbon are used for the better grades of cutlery and for a variety of purposes requiring high strength, oxidation and corrosion resistance. They must be fully hardened and free from surface imperfections to develop maximum corrosion resistance. With modifying elements such as nickel, molybdenum, and vanadium the steels are even more suitable for cutlery and articles such as valve parts and ball bearings where wear is severe. Steels containing carbon up to 2% are also used in tools, rolls, and dies to avoid excessive wear. Modifying alloys are commonly used. The steel can be annealed for machining and is hardened by oil quenching followed by tempering to secure appropriate properties.

Ferritic Chromium Steels—When the chromium content exceeds 16-17%, austenite formation is largely restricted as shown in Fig. 1 and 2, and the structure consists primarily of ferrite that is not transformed to austenite at elevated temperatures. The low carbon steel does not harden readily and can be cold worked to an unusual degree especially when the small percentage of carbon present is fixed with columbium or titanium. The steel containing 18% chromium is widely used on account of its great corrosion resistance, and higher chromium contents up to 28% are used for oxidation resistance at high temperatures. The latter steel is subject to grain growth at elevated temperatures and if so heated is quite brittle unless the steel is given a persistently fine grain size by the addition of nitrogen. These steels have found application in furnace construction, and heat exchangers for resistance to oxidation and sulphur-bearing gases at temperatures up to 2100°F., and for resistance to mine water and mixed acids at ordinary temperatures.

Higher carbon increases the oxidation and wear resistance, and a large proportion of the steel in the range of 15-30% chromium is used in the form of castings

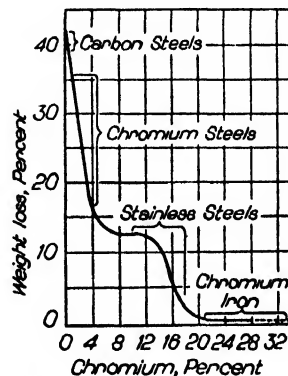


Fig. 4—Effect of increasing chromium on oxidation resistance.

with 1.00-2.50% carbon. High chromium cast iron is one of the most abrasion resistant of the ferrous materials, and is used for such parts as sand blast equipment and piercing points.

A more recently developed application of ferritic steel is the alloy containing 37% chromium and 7½% aluminum for resistors in electric furnaces. While the alloy has a low strength, it resists oxidation at temperatures up to 2370°F.

Austenitic Chromium Steels—Due to the sluggish manner in which high chromium steels transform, it is possible, by the addition of metals such as nickel, manganese, and copper, to produce and retain exceedingly persistent austenite by moderately rapid cooling from 1825-2190°F. The austenitic chromium steels have an extremely high order of corrosion and oxidation resistance. They have exceptionally good cold working properties, are adaptable to severe deep drawing operations, and are suitable for use in the cold rolled condition if high strength is required. The steels have the low magnetic susceptibility and the high coefficient of expansion typical of austenite. Due to their ease of fabrication by welding, bending, forming, or spinning, the austenitic steels have enjoyed the widest range of application of any of the stainless steels.

The most popular composition contains 18% chromium and 8% nickel. Several other steels ranging up to 25% each of chromium and nickel are also used. Higher chromium is required to gain further oxidation resistance, and more nickel is added to obtain greater austenite stability and greater strength at elevated temperatures. Steels similar to 18-8 have also been developed where manganese and copper are substituted for all or a part of the nickel. These steels have good drawing properties and are more resistant to sulphur-bearing atmosphere than the 18% chromium-8% nickel steels. The chromium-manganese steel has a structure consisting partially of austenite and partially of ferrite. Other additions are made to austenitic chromium steels for specific purposes. Columbium or titanium is added to prevent susceptibility to intergranular corrosion during heating in the range of 575-1650°F. Molybdenum, tungsten, and copper confer additional corrosion resistance. Aluminum and silicon may be used to increase the oxidation resistance. Selenium and sulphur improve the machinability.

The austenitic chromium steels are used primarily for acid resistance in chemical and food handling plants, for furnace parts, and for architectural trim. The corrosion resistance and high strength of cold worked austenitic chromium steel make possible the use of light box type structural members of great strength and stiffness. Although this type of construction is being developed for uses where weight is a primary factor, as in aircraft, railroad cars, and ships, it is evidently destined to play a large role in other applications.

Stainless Steel*

(Castings Not Included)

By Owen K. Parmiter†

Less than 20 years ago, the term "Stainless Steel" referred to but one type of corrosion resistant material. The steel contained 0.35% carbon and 13.50% chromium. Today, the number has increased to upwards of 60 different compositions including types for practically every application requiring a heat or corrosion resistant steel.

So rapid has been the progress in developing new combinations and types that it is difficult to decide at this time upon the relative importance and merits of many of them. Limited space confines this discussion to about 16 representative types whose value has been established. These are briefly described, special consideration being given to composition, heat treatment, and general physical properties.

Series of Straight Chromium-Iron Alloys—All of the corrosion resistant steels included in this series possess a comparatively low degree of heat conductivity and a high resistance to the softening action of heat, the combined effect of which makes forging somewhat difficult. In addition to this, the high carbon types harden readily in air after forging, which necessitates a softening or annealing operation before further fabrication. Each of the following "type compositions" requires heat treatment to bring out its maximum properties. Aside from those particular steels that require a definite hardening treatment, most of the various types are furnished by the manufacturer heat treated ready for use.

5% Chromium-Iron—This composition was developed as an intermediate type between ordinary carbon steel and stainless iron. It possesses properties that make it desirable for use in the oil refining industry. A number of modified compositions containing molybdenum, tungsten, aluminum, and copper are available.

Composition and Heat Treatment

C	Si	Mn	Cr	Mo-W-Al-Cu
0.05-0.25	0.50 max.	0.50 max.	4.00-6.00	Up to 1.00% of each as desired

Operation	Temp. Range, °F.	Approx Brinell Hardness No.
Forging.....	2000-1700	...
Annealing.....	1550-1575	150
Hardening.....	1800-1850, water	375
Tempering.....	Up to 1200—To suit purpose.	

Physical Properties of 5% Chromium-Iron

	Fully Annealed	Water Quenched 1800°F. Tempered 1100°F.
Yield point, psi.....	25,000 (min.)	145,000
Tensile strength, psi.....	60,000 (min.)	175,000
Elongation, % in 2 in.....	30 (min.)	18 0
Reduction of area, %.....		60 0
Brinell hardness No.....	170 (max.)	300
Specific gravity.....		7.78-7.82
Electrical resistivity.....	43 microhms per cm. ²	
Thermal conductivity.....	72% that of wrought iron	
Modulus of elasticity.....	30,000,000 lb.	
Izod impact, ft.-lb.....	90 (annealed)	

Turbine Blade and Valve Trim Type—In the heat treated condition this type

*Author's Note—This article is offered as a digest for quick reference. Complete details pertaining to heat and corrosion resistant materials can be found in *The Book of Stainless Steels*, published by The American Society for Metals.

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Types and Applications of Chromium-Iron Steels

Type	Elements Identifying Typical Compositions, %				Other Elements	General Applications
	C	Si	Mn	Cr		
5% Chromium	0.10	0.35	0.40	5.00		Fair resistance to heat and corrosion. Preheater tubes, dampers, still bottoms, pipes, bolts, studs, tie rods, and furnace parts.
Turbine Type	0.12	0.20	0.40	12.50	Ni 0.40	High tensile strength machinery. Turbine blades, valve parts, pump rods, pistons, cutlery and tableware.
Original Cutlery Type	0.35	0.20	0.35	13.50		Table knives, scissors, spatulas, cleavers, hatchets, pump shafts, pistons and valve trim.
Modified Cutlery Type	0.70	0.40	0.45	16.50		Butcher knives, pocket knives, dental and surgical instruments.
Ball Bearing Type	1.05	0.45	0.40	17.00		All purposes where maximum resistance to abrasion is required in a corrosion resistant steel. Balls, races, valve seats, all bearing surfaces.
Poppet Valve Type No. 1	0.50	2.75	0.50	8.75	V 0.15	Internal combustion engine valves.
Poppet Valve Type No. 2	0.45	0.90	0.40	10.00	Al 1.60	Especially exhaust valves for automobiles and airplanes.
18% Chromium-Iron	0.10	0.50	0.50	18.00	Ni 0.30 max.	A soft ductile material that does not work harden readily; not as resistant as "18-8", but useful for interior work.
28% Chromium-Iron	0.15	0.50	0.50	28.00	Ni 0.30 max.	For all applications where strength and toughness are secondary to high temperature resistance, such as furnace parts and glass molds.

(Hard Types
Martensitic and Semi-Martensitic)(Soft Types
Ferritic and Semi-Ferritic)

Types and Applications of Chromium-Nickel-Iron Steels (Austenitic)

Elements Identifying Typical Compositions					General Applications
C	Si	Mn	Cr	Ni	
Max.					
0.25	1.25	0.75	8.50	22.00	Adapted to salt water and sulphuric acid resistance, for ship parts, periscope tubes, pump shafts, and valve trim in the oil industry.
0.20	0.50	4.00	16.00	6.00	
0.20	0.50	0.40	18.00	8.00	Culinary utensils, flat tableware, jewelry, dental and surgical instruments not requiring a sharp edge.
0.25	2.50	0.60	20.00	25.00	Available in many modified forms. A general purpose corrosion resistant material. Very useful in tubing and sheet form. In cold drawn wire it makes excellent springs.
0.20	0.50	0.60	20.00	10.00	Highly resistant to heat oxidation and chemical corrosion. Used for furnace parts, retorts, and tubes. Retains its strength and resistance at temperatures up to 2000°F.
0.20	0.50	0.60	25.00	12.00	A well balanced and useful combination of chromium and nickel. Possesses many of the valuable properties of both the higher and lower alloy content materials. Excellent resistance to both heat and corrosion.
0.20	2.00	0.60	25.00	20.00	Retains its strength and resistance at high temperatures. Adapted for oil burner parts, oil refinery, chemical plant equipment, skid rails, rollers, and other furnace parts.
					A highly efficient heat resistant steel. Used for furnace doors, muffles, retorts, skids, tubes, heat exchangers, dampers, valves, and pump parts. Recommended for temperatures up to 2100°F.

"Modified Analysis" Stainless Steels for Special Purposes

Elements Added to Those Already Present	Percentage of Additional Alloys	Purposes for Which Additional Alloys Are Incorporated
Aluminum	4.00-4.50	Increases the electrical resistance. Greatly improves the resistance to scaling at high temperatures.
Copper	1.00-4.00	Improves resistance to corrosive action of dilute hydrochloric acid, also brine and ammonium chloride solutions.
Columbium	0.60-1.50	Action similar to titanium. Greatly increases resistance to intergranular corrosion.
Manganese	3.00-5.00	Improves ductility and resistance to impact. Has strong stabilizing action. Increases corrosion resistance.
Molybdenum	1.00-4.00	Similar to tungsten in its action. Increases resistance to sulphurous and phosphoric acids also brine and hypochlorite solutions.
Selenium	0.20-0.30	Imparts free machining properties without sacrificing toughness and strength.
Silicon	0.50-3.50	Produces better workability and welding properties. Increases resistance to oxidizing action of high temperatures
Sulphur	0.30-0.40	Combined in the form of certain sulphides it greatly improves machining properties.
Titanium	0.40-0.80	Reduces warpage in sheet form. Prevents precipitation of carbides and intergranular corrosion.
Tungsten	2.50-3.50	Acts as an inhibitor of intercrystalline attack. Increases strength at elevated temperatures. Improves resistance to sea water corrosion.

combines a high degree of strength and elasticity without any loss of toughness and machinability. Some resistance to corrosion, however, is sacrificed for this excellent balance of physical properties. In the cold rolled, work hardened state, this type is used extensively for the cheaper grades of cutlery.

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.12 max.	0.20	0.40	12.00-16.00	0.50 max.

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging.....	2000-1700	...
Softening.....	1400-1450	225
Annealing.....	1550-1600	165
Preheating.....	1450-1500	...
Hardening.....	1775-1825	400
Drawing.....	Up to 1200—Depending upon size and purpose.	

The U. S. Navy Department Specification for physical properties for heat treated turbine parts made from this steel is as follows:

Proof stress.....	70,000 psi. (min.)
Tensile strength.....	100,000 psi. (min.)
Elongation.....	20% in 2 in. (min.)
Reduction of area.....	60% (min.)
Izod impact.....	50 ft-lb. (min.)
Brinell hardness No.....	200-240

Typical Physical Properties

	Oil Quenched 1825°F. Tempered 700°F.	Oil Quenched 1825°F. Tempered 1200°F.	Annealed, 1600°F.
Yield point, psi.....	160,000	100,000	58,000
Tensile strength, psi.....	185,000	120,000	85,000
Elongation, % in 2 in.....	17.5	22.5	33.0
Reduction of area, %.....	60.0	70.0	70.0
Izod impact, ft-lb.....	50	60	100
Brinell hardness No.....	395	240	165
Rockwell hardness.....	43 C	99 B	88 B
Specific gravity.....		7.77	
Coefficient of expansion.....		0.0000105 (20-200°C.)	
Thermal conductivity.....		0.046 cgs. units	
Modulus of elasticity.....		30,000,000 psi. (approx.)	
Electrical resistivity.....		50 microhms per cm. ³	
Magnetic properties.....		Fair	
Maximum Brinell hardness No.....		400 (light sizes to 475)	
Corrosion resistance.....		Good	
Machinability.....		Good	

Original Cutlery Type—This is the original stainless steel described by Brearley in his patent. It serves as an ideal material for many purposes. In order to bring out its maximum resistance to corrosion, it is necessary to harden and then thoroughly grind and polish it. This type can be made reasonably hard but is not capable of the same intense hardness possible with carbon tool steel.

As this particular steel is air hardening, it must be annealed after forging if machine work is required. In all heating operations it is necessary to preheat and then hold longer at the required heat than with ordinary steel. Forging is accomplished with more difficulty than with carbon steel. Frequent reheating is advisable.

Grinding has an important bearing on the ability of hardened stainless steels to resist corrosion. Wet grinding is always preferred, and it must be deep and thorough. Every trace of scale and surface scale must be removed. Any remaining scale pits serve as seats for corrosion and an electrolytic action is set up which rapidly spreads over the surface of the material as rust.

Composition and Heat Treatment

C	Si	Mn	Cr
0.30-0.40	0.20	0.35	12.00-15.00

Operation	Temp. Range, °F.	Approx Brinell Hardness No.
Forging.....	2000-1700	220
Softening.....	1400-1450	185
Annealing.....	1575-1625	...
Preheating.....	1450-1500	550
Hardening.....	1775-1850	
Tempering.....	350- 900—To suit purpose.	

Typical Physical Properties

	Oil Quenched, 1825°F. Tempered 450°F.	Oil Quenched, 1825°F. Tempered 1250°F.	Annealed, 1600°F.
Yield point, psi.....	200,000	125,000	65,000
Tensile strength, psi.....	240,000	150,000	100,000
Elongation, % in 2 in.....	4.0	12.0	27.0
Reduction of area, %.....	8.0	40.0	60.0
Izod impact, ft-lb.....	10	25	.....
Brinell hardness No.....	500	300	185
Rockwell hardness.....	52 C	107 B	91 B

(Continued)

Specific gravity.....	7.77
Coefficient of expansion.....	0.0000109 (20°-200°C.)
Thermal conductivity.....	0.0334 cgs. units
Modulus of elasticity.....	30,000,000 psi. (approx.)
Electrical resistivity.....	50 microhms per cm. ²
Magnetic properties.....	Fair
Maximum Brinell hardness No.....	550 (approx.)
Corrosion resistance.....	Good (in hardened state)
Machinability.....	Good (in annealed condition)

Modified Cutlery Type—This type was developed in an endeavor to incorporate some of the advantages of carbon steel into stainless material without sacrificing the quality of resisting corrosion. In most respects it works quite similarly to the original cutlery type, except that a more intense hardness and a better cutting edge are possible. This modified composition for stainless cutlery is used principally in hot rolled double bevels.

Composition and Heat Treatment

C	Si	Mn	Cr	Mo
0.55-0.75	0.40	0.45	15.00-18.00	0.50 optional

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging.....	2000-1700	...
Softening.....	1400-1450	230
Annealing.....	1625-1675	195
Preheating.....	1450-1500	...
Hardening.....	1825-1925	600
Tempering.....	300- 800—To suit purpose.	

Typical Physical Properties

	Oil Quenched, 1850°F. Tempered 450°F.	Oil Quenched, 1850°F. Tempered 1250°F.	Annealed, 1650°F.
Yield point, psi.....	245,000	100,000	54,000
Tensile strength, psi.....	270,000	130,000	95,000
Elongation, % in 2 in.....	2.0	12.0	27.0
Reduction of area, %.....	3.5	30.0	45.0
Izod impact, ft.-lb.....	3	6	14
Brinell hardness No.....	545	285	185
Rockwell hardness.....	55 C	105 B	91 B
Specific gravity.....		7.73	
Coefficient of expansion.....		0.0000100 (20°-200°C.)	
Thermal conductivity.....		.....
Modulus of elasticity.....		.....
Electrical resistivity.....		75 microhms per cm. ²	
Magnetic properties.....		Fair	
Maximum Brinell hardness No.....		600 (approx.)	
Corrosion resistance.....		Very good (in hardened state)	
Machinability.....		Good (in annealed condition)	

Ball Bearing Type—This special composition is adapted for purposes where hardness and resistance to abrasion are required in a corrosion resistant steel. This type is capable of a hardness up to as high as 62 C Rockwell in small cross sections and in this state shows excellent noncorrosive properties.

It is recommended particularly for balls, valve seats, and wearing surfaces in general where maximum abrasion resistance is demanded in a stainless steel. It has found particularly valuable application in the oil industry for needle and check valve parts in oil lines. This type is the hardest form of stainless steel.

Composition and Heat Treatment

C	Si	Mn	Cr	Mo	V
0.90-1.10	0.45	0.40	15.00-18.00	0.60 optional	0.25 optional

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging	1850-1700	...
Softening	1450-1500	325
Semiannealing	1600-1650	250
Full annealing	1700-1750	225
Preheating	1400-1450	...
Hardening	1825-1925	(max.) 625
Tempering	300- 800—To suit purpose.	

18% Chromium-Iron—This nonhardening alloy is highly malleable and ductile. It is used for parts where great strength is secondary to corrosion resistance and workability. It is useful for drop forgings, cold upset articles, sheets and tubing. It does not work harden to the same degree as "18-8" and, therefore, is tougher after cold heading operations. This characteristic is of considerable advantage in many cases.

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.12 max.	0.50 max.	0.50 max.	16.00-18.00	0.50 max.

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging	2000-1600	...
Softening	1375-1400	180
Annealing	1400-1450	149
Preheating	1400-1450	...
Hardening	1775-1825—Oil quenched in light sections.	250

Typical Physical Properties at Room Temperatures Annealed State

Yield point, psi.....	45,000-55,000
Tensile strength, psi.....	75,000-85,000
Elongation, % in 2 in.....	35-45
Reduction of area, %.....	60-70
Brinell hardness No.....	135-170
Specific gravity	7.70
Coefficient of expansion (per °C., 0°C.-600°C.).....	0.0000117
Thermal conductivity	Approx. ½ that of ordinary steel.

28% Chromium-Iron—This 28% chromium alloy is recommended for high temperature applications. While it shows a remarkable resistance to oxidation at temperatures up to about 2000°F., it has a tendency to lose strength at such elevated heats and, therefore, should not be used for installations where high strength and toughness are requisites. It possesses excellent noncorrosive properties and is recommended for its resistance to acid mine water, mixed acids, and to sulphur gases at high temperatures.

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.35 max.	0.50 max.	0.50 max.	23.00-30.00	0.50 max.

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging	2100-1500	...
Softening	1300-1350, air-cooled	200
Annealing	1550-1600, water	160
Preheating	1500-1700	...
Hardening	Cannot be hardened by thermal treatment	

*Average Physical Properties at Room Temperatures
Forged, Rolled, and Annealed*

Yield point, psi.....	45,000-60,000
Tensile strength, psi.....	75,000-95,000
Elongation, % in 2 in.....	25-35
Reduction of area, %.....	45-65
Brinell hardness No.....	160-200
Specific gravity	7.60
Coefficient of expansion, 32°- 212°F.....	0.0000056
32°-1832°F.....	0.0000074
Thermal conductivity	About 50% that of wrought iron
Electric resistivity	385 ohms per circular mil foot

Series of Chromium-Nickel Iron Alloys—The representative types contained in this group of highly resistant chromium-nickel alloys include various combinations of chromium and nickel in amounts ranging from 8.00-25.00% of each. Many modified forms of these high chromium-nickel steels have been developed for special purposes. These include additions of aluminum, copper, columbium, manganese, molybdenum, selenium, silicon, sulphur, titanium, and tungsten. These additional alloys have a marked effect upon the structure and heat and corrosion resistance of the resultant steel but in most cases little or no effect upon its forging or heat treatment.

All of the high chromium-nickel combinations are austenitic and possess the usual characteristics of that type, namely, low heat conductivity, comparatively high coefficient of expansion, nonmagnetic properties, inability to harden by heat treatment, good workhardening properties, and satisfactory toughness. Like other austenitic steels with the exception of the 8.50% Cr-22.00% Ni type, they are annealed or fully softened by cooling rapidly from a high temperature, usually about 2000°F. These steels of the austenitic group require prolonged soaking during both the preheat and initial heat for forging.

8.50% Cr-22.00% Ni Type

(Highly Resistant to Heat, Corrosion and Abrasion)

Composition and Heat Treatment

C	Si	Mn	Cr	Ni	Cu
0.25 max.	1.25-1.50	0.60-0.90	7.00-10.00	21.00-23.00	1.00-1.50

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Preheating	1600-1800 (soak well)	...
Forging	2050-1800 (do not soak)	...
Annealing	1650-1750 (cool slowly)	150
Hardening	Only by cold working	...
Do not soak at temperatures above 1800°F.		
Do not forge at temperatures below 1600°F.		

Typical Physical Properties in Annealed Condition

Yield point, psi.....	50,000- 65,000
Tensile strength, psi.....	90,000-100,000
Elongation, % in 2 in.....	25- 35
Reduction of area, %.....	45- 65
Brinell hardness No.....	165-190
Specific gravity	8.00
Coefficient of expansion, per °C.:	
20°-300°C.....	0.0000168
300°-600°C.....	0.0000180
600°-900°C.....	0.0000200
Electrical resistance	0.520 ohms per mil ft.
Specific heat	0.07
Thermal conductivity	1/14 that of copper
Modulus of elasticity.....	28,000,000-30,000,000 lb.
Magnetic properties	Nonmagnetic

18.00% Cr-8.00% Ni Type

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.08-0.20	0.75 max.	0.60 max.	17.00-19.00	7.00-9.00

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging	2350-1750	...
Partial softening	1600-1700	185
Complete softening	2000-2200 (cool rapidly)	148
Hardening	By cold working only.	
Drawing (after cold working) ..	Up to 750°F. improves ductility.	

Physical Properties at Room Temperatures
(Softened Condition)

Yield point, psi.....	30,000-35,000
Tensile strength, psi.....	85,000-95,000
Elongation, % in 2 in.....	55- 60
Reduction of area, %.....	70- 75
Brinell hardness No.....	145-160
Rockwell hardness (B scale).....	80- 84
Izod impact, ft-lb.....	115-120
Specific gravity	7.93
Thermal conductivity	0.0390 cgs. units (100°C.)
Coefficient of expansion.....	0.000020 (0°-1000°C.)
Scaling point	1700°F.
Specific heat	0.118 cal. per °C.
Melting point	2700°F.
Deep drawing properties.....	Very good
Electrical resistivity	91 microhms (100°C.)
Magnetic properties	Practically nonmagnetic
Modulus of elasticity, psi.....	29,000,000
Structure	Austenitic

20.00% Cr-25.00% Ni Type
(Heat Resistant, High Strength Alloy)

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.25 max.	2.25-3.00	0.50-0.70	19.00-21.00	24.00-26.00

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging	2050-1700	...
Complete softening.....	2000-2100*	175
Hardening	Only by cold working.	

*Do not soak at this temperature; cool rapidly.

Typical Physical Properties in Softened Condition

Yield point, psi.....	45,000- 50,000
Tensile strength, psi.....	90,000-110,000
Elongation, % in 2 in.....	30- 35
Reduction of area, %.....	35- 45
Brinell hardness No.....	160-185
Izod impact, ft-lb.....	50- 90
Specific gravity	7.85
Coefficient of expansion, per °C.:	
20°-300°C.....	0.0000163
300°-600°C.....	0.0000180
600°-900°C.....	0.0000200
Electrical resistance	102.2 ohms per cm. ² × 10 ⁴ at 100°F.
Modulus of elasticity.....	About 30,000,000 lb.

25.00% Cr-12.00% Ni Type
(Heat Resistant, High Strength Alloy)

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.20 max.	0.75 max.	1.00 max.	22.00-26.00	11.00-13.00

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Preheating	1550-1800 (soak well)	...
Forging	2250-2000 (soak well)	...
Annealing	2000-2100, air cool*	165
Hardening	Only by cold working.	
*Do not soak at annealing heat. Do not forge below 1800°F.		

Average Physical Properties in Annealed State

Yield point, psi.....	40,000- 60,000
Tensile strength, psi.....	90,000-110,000
Elongation, % in 2 in.....	45- 55
Reduction of area, %.....	50- 60
Brinell hardness No.....	150-200
Specific gravity	7.83
Thermal conductivity	About 40% that of ordinary steel
Resistance to scaling	Up to about 2100°F.
Coefficient of expansion, per °F., 32°F.-932°F.....	0.0000096
Specific electrical resistance.....	80 microhms per cm.*

25.00% Cr-20.00% Ni Type
(Heat Resistant, High Strength Alloy)

Composition and Heat Treatment

C	Si	Mn	Cr	Ni
0.25 max.	0.70-1.50	0.50-0.70	24.00-26.00	19.00-21.00

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Preheating	1700-1800 (soak well)	...
Forging	2200-2050 (soak well)	...
Annealing	2000-2100*	165
Hardening	Only by cold working.	
*Do not soak at annealing heat. Do not forge below 1800°F.		

Typical Physical Properties in Annealed Condition

Yield point, psi.....	45,000- 55,000
Tensile strength, psi.....	100,000-110,000
Elongation, % in 2 in.....	45- 55
Reduction of area, %.....	50- 60
Brinell hardness No.....	155-175
Charpy impact, ft.-lb.....	35- 65
Coefficient of expansion, per °F.:	
32°- 600°F.....	0.0000085
32°-1700°F.....	0.000010
Thermal conductivity	Approx. 40% that of ordinary steel
Specific gravity	7.93

Free Machining Types—Two general types comprise this group; one a free cutting 14.00% chromium-iron, and the other a free cutting "18-8" steel. Selenium, phosphorus, and sulphur in the form of metallic sulphides are used in various combinations to produce the desired crisp machining effect.

Free Machining 14.00% Chromium-Iron

Composition and Heat Treatment

C	Si	Mn	S	Cr	Mo
0.12 max.	0.25	0.45	0.350	12.00-15.00	0.40

Operation	Temp. Range, °F.	Approx. Brinell Hardness No.
Forging*	2200-1800	...
Annealing	1300-1450, air cooled	185
Annealing	1300-1450, furnace cooled	165
Preheating	1450-1500	...
Hardening	1825-1850	325
Tempering	Up to 1200°F.—To suit purpose.	

*Forging temperature for this type is considerably higher than for similar type containing low sulphur.

Typical Physical Properties in Annealed State

Yield point, psi.	50,000-65,000
Tensile strength, psi.	75,000-90,000
Elongation, % in 2 in.	25-30
Reduction of area, %	50-60
Isod impact, ft-lb.	50
Brinell hardness No.	180-190
Rockwell hardness	85-90
Specific gravity	7.75
Coefficient of expansion	0.0000104 (20°-200°C.)
Thermal conductivity	0.046 cgs. units
Electrical resistivity	50 microhms per cm.*
Magnetic properties	Fair
Maximum Brinell hardness No.	350
Corrosion resistance	Fair
Machinability	Very good
Recommended uses	Screw machine work

Free Machining "18-8"

Composition and Heat Treatment

C	Si	Mn	Cr	Ni	P	S
0.08-0.20	0.75 max.	1.00 max	17.00-19.00	7.00-9.00	0.125	0.250

The improved machinability of this type over the standard "18-8" composition has been obtained with a slight loss of corrosion resistance, but without sacrificing strength or toughness. It can be drilled, tapped, threaded, and machined with ordinary machine tools and practice. In automatic screw machines, recommended speeds are about 70% of those used on ordinary screw stock. This free machining type is recommended for general machine parts, including screws, bolts, nuts, pump shafts, valve trim, bushings, and spindles.

Free Machining "18-8" shows about the same physical properties as the standard composition and the same heat treating instructions apply.

Wrought Heat Resisting Steels*

Introduction—Carbon steels, which offer a wide selection of mechanical properties at room temperature, lose their valuable characteristics at elevated temperatures with the result that the mechanical properties tend to seek equilibrium and the effect of initial heat treatment is more or less eliminated, depending on service temperature. Wherever carbon steels are unsatisfactory for use at elevated temperatures either because of insufficient strength or lack of satisfactory corrosion or oxidation resistance, it is customary to turn to alloy steels, either low alloy additions of molybdenum, chromium, or silicon, or for more severe service conditions, the higher chromium stainless alloys such as 12%, 17%, 27% Cr, 18% Cr-8% Ni, 25% Cr-12% Ni, 25% Cr-20% Ni, and modifications thereof. The modifications may incorporate additions of such elements as titanium, columbium, molybdenum, tungsten, or silicon for specific purposes such as stabilizing carbides, increasing strength or scaling resistance. Nitrogen may be added to retard grain growth, particularly in the 27% chromium alloy. Other alloys having less than 50% iron content, for example, nickel-base alloys such as 35% Ni, 15% Cr; 65% Ni, 15% Cr; and 80% Cr, 20% Ni are used for heat resisting purposes especially for metallic resistors, furnace parts, carburizing boxes and are covered in other articles in this Handbook.

Carbon, one of the most mobile elements encountered in ferrous metallurgy, because of its atomic dimensions, is unstable at elevated temperatures both chemically and constitutionally; witness, for example, such effects as carbide aging in mild steel even at room temperatures, the prevalence of decarburization as compared to "dechromiumization" or "desiliconization," and latitude of properties obtained by heat treating eutectoid steel as compared to mild steel.

For this reason carbon is of little benefit in wrought steels for use at elevated temperatures and, except in special cases such as in carbon steel superheater tubes, alloy bolt steels and valve steels, is usually kept below 0.20% and in some cases below 0.10%. Most of the other elements described are present in solid solution in the austenite or ferrite, depending on the nature of the alloy. Thus chromium, for example, affects an inherent change in the properties of the metal apart from modifying the structural habits, that is, pearlite or troostite formation. As the chromium content of a 0.1% carbon steel is increased, one of the first noticeable contributory effects is the increased sluggishness of phase changes; 5% chromium steel is air hardening in much larger sections than mild steel because the austenite or high temperature modification persists on cooling much more than is the case for mild steel and does not usually transform until near room temperatures to yield a martensitic product. Supplementary, but entirely unrelated to this effect just described, the addition of chromium tends to reduce the rate of attack of many reagents on the metal and at about 11% addition of chromium, this change becomes so marked that the iron alloys containing more than 11% chromium have been termed "stainless steels."

Chromium is a ferrite stabilizer, that is, it acts to increase the temperature range in which ferrite is stable and with the addition of about 16% chromium, and a low carbon content, the austenite or high temperature constituent is almost completely eliminated. A higher chromium content than 16% renders the metal nonresponsive to heat treatment in the ordinary manner practiced with steel but does not prevent grain growth at the higher temperatures. Nickel is an austenite former and tends to offset the effect of chromium. The addition of about 8% nickel to an 18% chromium alloy results in the formation of austenite as the stable phase in the heat treating range of temperatures and as a result of the quantity of alloying elements present, the austenitic phase persists on cooling to room temperatures. Deforming this border-line 18-8 composition at temperatures below 300°F. causes the austenitic phase (nonmagnetic) to break down and partially transform to the ferritic phase (magnetic) but on reheating to temperatures above 1400°F., ferrite quickly reverts to austenite. Larger quantities of nickel yield completely stable austenite which does not transform on cold working.

Chromium is a carbide forming element and will readily usurp the place of iron in cementite to form a series of mixed iron carbide-chromium carbide inter-

*Prepared for the Subcommittee on Wrought Heat Resisting Steels by H. D. Newell and John J. B. Ruthertford, The Babcock & Wilcox Tube Co. The membership of the subcommittee was H. D. Newell, Chairman; R. H. Aborn, F. B. Foley, R. Franks, S. M. Heck, C. M. Johnson, E. R. Johnson, V. N. Krivobok, and N. B. Pilling.

†See the article in this Handbook on the Constitution of Iron-Chromium-Nickel Alloys.

mediate phases. Since the chromium carbide is more stable, the solubility of carbon in iron-chromium alloys is lower than in iron. About 0.03% carbon is soluble in 18-8 (austenite) at 1400°F. whereas in iron at the same temperature (also austenite) about 0.9% carbon is soluble in the austenite.

These features serve in the interpretation of the effect of temperatures on the structural behavior of these alloys. The 12% chromium alloy is amenable to heat treatment, is air hardening and fairly resistant to chemical and oxidation attack. The 17% chromium alloy is not normally amenable to heat treatment but can be hardened to a limited extent by air cooling from high temperatures (above 1800°F.). (It can be hardened in presence of sufficient carbon and/or nickel). It is more resistant to oxidation than the 12% chromium alloy. The 27% chromium steel is not amenable to heat treatment but is susceptible to embrittlement if held in the range 800-1000°F. and then tested at room temperature (this effect has been associated with the formation of an iron-chromium compound); it is still more resistant to oxidation than the other ferritic alloys. Certain of the lower chromium steels also develop cold brittleness after long heating in this range of temperature, for example 17% chromium-iron and 5% chromium steel, toughness is returned on warming or by heating to 1200°F. and rapidly cooling. Among the austenitic steels, 18-8, 25-12, and 25-20, those containing higher chromium content are more resistant to oxidation, the additional nickel content gives greater resistance to creep at elevated temperatures, to oxidation, and to chemical attack in certain media.

Resistance to Oxidation—The first prerequisite of a steel for use at elevated temperatures is resistance to oxidation. Table I gives comparative scaling temperatures for a group of steels. It should be noted that this scaling temperature is

Table I
Comparative Scaling Temperatures

Type and Code	No.	C	Mn	Nominal S	Composition, % P	Si	Cr	Ni	Scaling Temp., °F.
12 Cr.....	410	0.10	0.5	0.02	0.02	0.3	12	..	1300
17 Cr.....	430	0.10	0.5	0.02	0.02	0.3	17	..	1550
27 Cr.....	446	0.15	0.7	0.02	0.02	0.3	27	..	2100
18-8.....	302	0.10	0.5	0.02	0.02	0.5	18	8	1650
25-12.....	309	0.15	1.0	0.02	0.02	0.7	25	12	2100
25-20.....	310	0.15	1.0	0.02	0.02	0.7	25	20	2150

based on rather arbitrary standards and serves to indicate generally the lowest temperature at which, on prolonged heating in a strongly oxidizing atmosphere, a scale will form of sufficient thickness to cause flaking or spalling. These steels will oxidize at much lower temperatures forming a series of temper colors until a thin, black adherent scale layer is formed but this reaction tends to cease whereas above the scaling temperature, spalling causes progressive deterioration, thus reducing service life or making mandatory a selection of higher alloy for economical and continued operation. Compositional modifications, such as the addition of silicon or aluminum, changes the scaling temperature by changing the nature of the scale layer. A similar effect, also related to the nature of the scale product, concerns the type of atmosphere in which the metal is tested. Table II contains the results of

Table II
Scaling Tests

Test Conditions	Types				
	12 Cr	17 Cr	27 Cr	18-8	25-12
Gain in Weight, mg. per sq. cm.					
50 hr. 1650°F. in Air.....	0.7	0.7	..	..	..
50 hr. 2010°F. in Air.....	250.0	7.0	2.5	15.0	9.0
50 hr. 1800°F. in Hydrogen Sulphide	1000.0	930.0	820.0	...	...

scaling tests conducted in a highly oxidizing atmosphere and, for comparison, similar tests conducted in an atmosphere of hydrogen sulphide. At these test temperatures, the chromium-rich oxide is refractory and reduces further chemical reaction while the complex sulphides formed are liquid and promote interaction between the gas and metal phases. In reducing atmospheres, where quantities of carbon monoxide are present, the scale formed is lower in chromium and therefore, offers less pro-

Table III
Short Time Tensile Tests on Wrought Alloys*

(1 hr. at temperature—pulled 0.05 in. per min.)

Material	Temp. °F	Ultimate, psi.	Elongation, % in 2 in.	Red. of Area, %
12 Cr. (Type 410)	Room	89,370	32.0	71.4
C 0.12, Mn 0.42,	200	83,170	29.0	75.0
P 0.014, S 0.020,	400	76,580	28.0	76.0
Si 0.18, Cr 12.27,	600	72,850	25.0	73.6
Ni 0.204 (annealed)	800	68,140	25.0	70.3
	900	54,700	26.0	73.2
Brinell hardness 187	1000	44,750	26.0	77.5
	1100	34,700	43.0	87.3
	1200	24,810	50.0	92.9
	1300	15,160	58.0	95.3
	1400	9,200	68.0	97.9
	1500	9,450	78.5	73.4
	1600	9,740	69.0	41.9
17 Cr. (Type 430)	Room	76,580	32.0	74.4
C 0.07, Mn 0.30,	200	71,880	30.0	74.0
P 0.013, S 0.020,	400	67,140	27.5	75.8
Si 0.29, Cr 16.56,	600	63,900	26.0	75.2
Ni 0.157	800	56,190	29.0	74.6
	900	48,980	34.0	75.6
Brinell hardness 179	1000	35,800	35.5	84.4
	1100	26,850	55.0	90.8
	1200	18,650	61.5	97.1
	1300	11,440	67.6	99.1
	1400	7,460	70.0	99.5
	1500	5,090	83.0	99.8
	1600	3,480	188.0	98.4
17 Cr. (Type 446)	Room	93,480	26.0	69.6
C 0.10, Mn 0.74,	200	83,170	19.5	53.5
P 0.021, S 0.014,	400	82,380	19.0	47.5
Si 0.13, Cr 30,	600	80,630	20.5	41.6
Ni 0.57	800	70,520	15.5	47.2
	1100	39,280	47.0	73.2
Brinell hardness 163	1200	24,210	47.0	85.2
	1300	10,860	57.0	90.7
	1400	6,890	80.0	93.0
	1500	4,245	133.0	97.7
	1600	3,355	165.0	98.8
18-8 (Type 304)	Room	91,500	68.0	75.5
18% Cr, 9% Ni,	200	78,600	59.0	79.5
0.07% C Max	400	70,250	47.0	73.1
	600	71,430	46.5	70.6
	800	67,025	45.2	68.8
	900	64,480	40.2	69.1
	1000	61,825	44.5	69.0
	1100	53,740	40.7	64.8
	1200	44,375	46.7	64.1
	1300	35,620	50.7	58.2
	1400	23,650	53.2	51.0
	1500	17,210	54.5	47.2
	1600	14,500	50.0	45.0
25-12 (Type 309)	Room	79,880	71.0	81.0
C 0.082, Mn 0.97,	200	72,520	56.0	80.0
P 0.014, S 0.013,	400	66,890	52.5	78.0
Si 0.38, Cr 22.94,	600	66,530	47.5	75.0
Ni 12.72	800	66,400	48.0	72.0
	900	61,680	47.0	72.0
	1000	60,920	48.0	69.0
	1100	54,920	41.5	59.6
	1200	44,680	28.0	31.0
	1300	36,570	27.5	28.0
	1400	28,610	25.0	31.0
	1500	21,470	38.0	33.0
	1600	15,970	29.5	32.0
25-20 (Type 310)	Room	82,380	55.0	79.0
C 0.07, Mn 1.22,	300	73,350	51.5	78.0
P 0.023, S 0.021,	500	69,870	45.0	75.0
Si 0.35, Cr 24.99,	700	70,620	48.0	73.0
Ni 20.46	900	68,120	50.5	71.0
	1000	66,760	50.0	67.0
	1100	60,170	41.0	45.0
	1200	47,500	24.0	29.0
	1300	41,190	24.0	26.0
	1400	31,950	26.5	27.0
	1500	24,360	37.0	37.0
	1600	17,900	33.0	46.5

*.505 in. dia. x 2 in. gage length specimens.

tection; furthermore, if carburization occurs, since carbon combines preferentially with chromium, the surface of the metal is depleted in effective chromium content and scales more rapidly. Mention may be made of the fact that under repeated heating and cooling, the ferritic stainless steels tend to scale less than austenitic steels owing to their lower coefficient of thermal expansion.

Mechanical Properties—In order to determine the mechanical properties of metals at elevated temperatures, two types of test are customarily practiced, short time tensile and creep tests. The departure from room temperature testing technique is necessitated by the fact that at temperatures above about 700°F. a new phenomenon of flow becomes operative which requires study on the basis of stress-strain-time factors at each temperature. The short time tensile test is similar in procedure to the ordinary tensile test except that the specimen is enclosed in a furnace designed to give a uniform temperature distribution held for a period of 30 min. to one hour, then, still maintained at temperature, it is pulled to fracture. Table III contains a compilation of data obtained by this type of test.

Creep Strength—Creep strength data are usually computed on the basis of the load required to obtain an elongation of 1% in either 10,000 hours or 100,000 hours depending on service requirements. The carbon steels may be satisfactory up to 800°F. or even to 1000°F.; under low stresses, low alloy steels are commonly used between 800°F. and 1100°F., above 1100°F. the extra strength and corrosion resistance of the stainless alloys generally become necessary. Table IV contains creep strength values for the stainless alloys. It should be noted that stress required to obtain a flow rate of 1% in 10,000 hours is greater than, but not in direct proportion to, the stress required for 1% in 100,000 hours. The practice of extrapolating the data in this table to different temperature ranges, flow rates, or composition is not recommended.

Table IV
Creep Strength Data

Temp., °F.	0.11% C 12 Cr	0.10% C 17 Cr	0.20% C 27 Cr	0.08% C 18-8	25-12	0.12% C 25-20
<i>Stress causing creep rate of 1% elongation in 10,000 hours</i>						
900	.....	.....	.....	24,000	.....	.....
1000	13,000	8,500	.....	17,000	.....	.....
1100	5,200	5,200	.....	11,550	.....	.....
1200	2,100	2,100	1,600	7,000	.....	7,400
1350	1,400	1,200	400	3,000	.....	3,300
1500	.....	.....	.....	850	.....	1,100
<i>Stress causing creep rate of 1% elongation in 100,000 hours</i>						
800	.....	.....	.....	25,300	.....	.....
900	.....	.....	.....	18,000	.....	.....
1000	10,000	7,000	.....	11,500	.....	.....
1100	4,000	4,500	.....	7,100	.....	.....
1200	1,600	1,600	1,000	4,250	.....	5,400
1350	900	900	180	1,600	.....	2,800
1500	.....	.....	.....	.....	.....	800

The superior creep resistance of the austenitic alloys indicates the advantage of this type for service at temperatures above 1000°F. Relatively small additions of molybdenum and silicon, for example have been observed to alter considerably the creep strength values of the various chromium and chromium-nickel alloys. In the marginal austenitic alloys, this may be due to ferrite formation brought about by the additional element. The unexpected decrease in creep resistance of the higher chromium ferritic alloys at 1200 and 1350°F. may be associated with the peculiar temper aging which occurs in this range, or even with the formation of an iron-chromium compound, since it is generally regarded that structural instability lowers creep resistance. Further, it appears that fundamentally the body-centered cubic atomic lattice arrangement (alpha ferrite) is less creep resistant than the face-centered atomic lattice arrangement (austenitic or gamma iron).

F. H. Norton has summarized his early creep test experiments as follows:

The results obtained on steels at temperatures over 1000°F. lead to the following conclusions:

1. The high chromium ferritic stainless steels have distinctly inferior creep resistance as compared with austenitic stainless steels.
2. The face-centered structure of the austenitic steels seems to offer a distinctly greater resistance to creep than the body-centered type.

3. The high chromium, high nickel type of austenitic steel seems to offer by far the most advantages in regard to creep resistance, heat resistance, and permanency of structure.
4. An increase in chromium content in ferritic stainless steel above 18% seems to decrease the creep resistance.
5. No evidence is found for a cessation of creep as the load is decreased, and the flow rate seems to decrease with the load in an exponential manner.

Fatigue Stresses—In view of the fact that rapid intermittent stresses (fatigue stresses) may have a similar effect at elevated temperatures as they have at normal temperatures, and since pulsating stresses occur at elevated temperatures in some types of service, research on this subject may appear advisable. The data in Table V are from a recent paper (J. S. Kinney, A.S.T.M. Preprint No. 46, 1938) on fatigue properties at elevated temperatures.

Table V
Fatigue Strength at Elevated Temperatures

Composition %: C 0.10, Mn 0.29, P 0.014, S 0.019, Si 0.31, Ni 0.38, Cr 12.30.
Condition: Annealed, 5 hr. 1175°F. furnace cooled to 570°F. then air cooled.

Mechanical Properties at Room Temperature

	Tensile Strength, psi. 11,700	Yield Point, psi. 80,000	Elong. in 2 in., % 23.5	Red. of Area, % 67.9
Temperature	Room	700°F.	850°F.	1000°F.
Endurance Limit, lb/sq. in. to 10 ⁻⁷ cycles.	58,000	49,000	43,500	27,200

Design—Permanency of the stainless alloys at elevated temperatures may be judged by oxidation and creep resistance values shown but numerous other physical properties are required by the engineers to estimate behavior at temperature rather than length of life. A group of such properties, which are believed to be quite reliable with proper interpretation, are included in Table VI. Most of these properties can be modified to a considerable extent by cold working. For example, 18-8

Table VI
Physical Characteristics of the Stainless Steels
Annealed Condition

	Types					
	12 Cr	17 Cr	27 Cr	18-8	25-12	25-20
Melting Range—Top, °F.....	2790	2750	2750	2590	2570	2600
Bottom, °F.....	2750	2710	2710	2550	2530	2550
Specific Gravity, g./cc.	7.65	7.57	7.49	7.92	7.83	7.9
lb./in. ³	0.276	0.273	0.270	0.286	0.283	0.285
Specific heat, cal./°C./g. 0-100°C.	0.11	0.11	0.11	0.12	0.12	0.13
Electrical resistivity, 70°F.....	57	59	67	70	78	80
Microhms/cm. ¹ 1200°F.....	109	115	115	117	115	117
Thermal conductivity cal./cm. ² /sec./°C./cm., at 100°C..	0.0595	0.0583	0.0500	0.390	0.03-0.04	0.039
B.t.u./ft. ² /hr./°F./in., at 212°F..	173	169	145	113	87-116	113
cal./cm. ² /sec./°C./cm., at 500°C..	0.0688	0.0624	0.0583	0.0515		
B.t.u./ft. ² /hr./°F./in., at 932°F..	199	181	169	150		
Coefficient of thermal expansion per °F.×10 ⁻⁴ , 32- 212°F.	6.1	6.0	5.9	9.6	8.3	
32- 932°F.		6.7	6.3	10.2	9.6	
32-1112°F.	6.65					
105-1320°F.						9.2
70-1832°F.						10.6

when severely cold worked has an expansion coefficient similar to the 17 Cr type by virtue of the change from the nonmagnetic to the magnetic condition but at temperatures above about 800°F. this change does not apply. In general, cold working is of little consequence in these alloys when used at elevated temperatures because of automatic stress relieving effects. Another factor concerning heat conductivity which is not shown in the tables is the tenacity of the oxide scale layer which frequently has been observed to offer greater resistance to heat transfer than the metal itself. In the use of bimetallic linings, heat transfer can be readily calculated if, for example, mild steel and stainless steel are welded together but in the

case of a fitted lining within which an appreciable scale layer exists, it is impossible to calculate heat transfer.

Because of the variety of design problems involved in the application of these materials to heat resisting structures, and lack of uniform methods of applying safe stress values, it is obvious that each application is a problem in itself as to selection of material for the service requirements and proper design for expected life of equipment.

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Heat Resisting Castings*

(Chromium-Nickel-Iron Alloys)

All heat resisting alloys are essentially alloys of iron and chromium in which the chromium serves to inhibit high temperature corrosion. In addition to iron and chromium, most heat resisting alloys also contain nickel which has been added to intensify the action of the chromium and to enhance the physical prop-

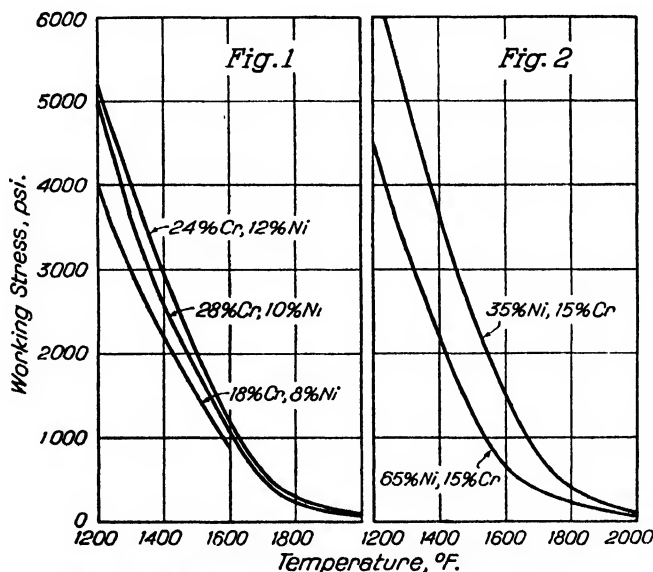


Fig. 1 and 2—Design strength for chromium-nickel alloys.

erties of the metal. The chromium content varies from about 12-30% and the nickel content may be as low as 8% or as high as 65%. Typical compositions are as follows:

18% Cr—8% Ni.	Balance principally iron
24% Cr—12% Ni.	Balance principally iron
28% Cr—10% Ni.	Balance principally iron
25% Cr—20% Ni.	Balance principally iron
18% Cr—65% Ni.	Balance principally iron
18% Cr—35% Ni.	Balance principally iron
20% Cr—35% Ni.	Balance principally iron
18% Cr	Balance principally iron
28% Cr	Balance principally iron

In the following discussion, alloys containing more nickel than chromium will be referred to as *nickel-chromium* alloys. Those in which chromium predominates will be called *chromium-nickel* alloys and those containing only chromium and iron will be designated *straight chromium* alloys.

Chemical Stability—Of the several alloys available for high temperature service, some are more stable than others in their resistance to chemical attack depending upon the environment in which they are to function. The most common forms of chemical action encountered in commercial heating practice are oxidation, sulphurization, and carburization. These factors acting together or independently

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may cause premature failure unless they have been carefully considered in selecting the alloy. Under purely oxidizing conditions any one of the three types of alloys mentioned may be used, the choice depending upon the temperature and the physical properties of the metal at elevated temperature (to be discussed later).

Under reducing conditions (in the absence of sulphur compounds) the nickel-chromium alloys are generally preferred because these alloys do not carburize readily.

In the presence of sulphur compounds, it is customary to select one of the chromium-nickel alloys. The extent to which sulphur may influence corrosion depends upon the amount present, the temperature, and the form in which it exists, usually SO_2 or H_2S . The subject of high temperature corrosion by sulphur is not well enough understood to permit other than a few general remarks, but practical experience indicates that chromium-nickel alloys are more resistant than nickel-chromium alloys and not infrequently the only alloys that can safely be

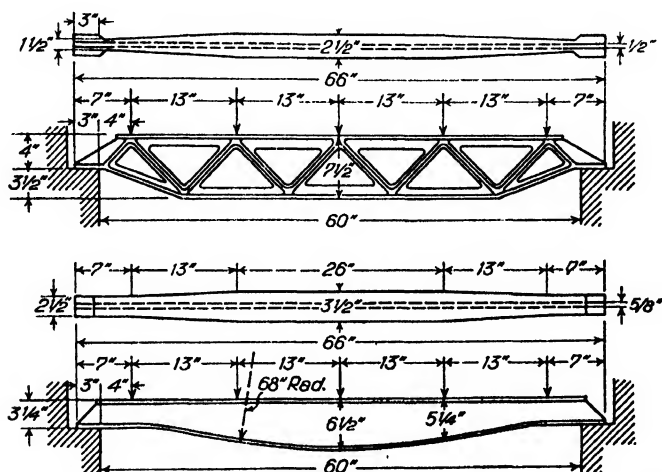


Fig. 3—Comparison of solid and trussed beams having the same load carrying capacity. Weight of beam above 75 lb.; beam below 120 lb.

used in furnaces fired with high sulphur content fuels. In general it is assumed that harmful compounds will be present if the fuel contains in excess of 1% sulphur. It is further the general opinion that the higher chromium to nickel ratio is more important under reducing than under oxidizing conditions.

High Temperature Strength—Next in importance to the question of chemical stability at high temperature is that of high temperature strength. It would be useless to select an alloy on the basis of high temperature strength alone because the physical strength of the material would be discounted by the loss of section due to progressive surface deterioration where this occurs. Conversely a material offering maximum resistance to corrosion and lacking in high temperature strength would lead to premature structural failure. But where more than one alloy is known to possess adequate resistance to corrosion under a particular set of conditions the choice should obviously be based upon physical characteristics and cost.

The straight chromium alloys compare unfavorably with the chromium-nickel and nickel-chromium compositions in the matter of high temperature strength under conditions of sustained loading. For this reason and because they may be subject to embrittlement at temperatures above 1200°F. and to grain growth at higher temperatures, the straight chromium alloys find a limited field of usefulness in high temperature applications.

Because of their nickel content the chromium-nickel alloys are in some respects more stable at high temperature than the straight chromium alloys. While these alloys may become less ductile under prolonged heating they do not become actually brittle in their cast forms unless the carbon content is sufficiently high

to permit excessive carbide precipitation at the grain boundaries. Brittleness from this cause should not be mistaken for brittleness due to carburization to which the chromium-nickel alloys are more or less susceptible, the rate increasing as the nickel content is lowered. Carbon exerts a profound strengthening effect in all chromium-nickel alloys which is achieved at the expense of ductility. For this reason it is generally preferable to limit the carbon content to that shown in the following table:

Chromium, %	Nickel, %	Carbon, % Max.
18	8	0.20
28	10	0.35
24	12	0.50

Of the above alloys, the 18-8 material is most susceptible to embrittlement due to carbide precipitation and carburization and for this reason it is not widely used at high temperature in cast forms.

Fig. 1 gives recommended design strength values for the most commonly used chromium-nickel alloys with carbon contents as indicated above.

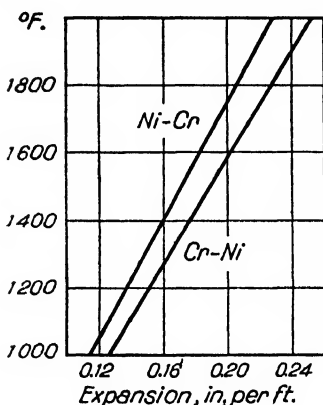


Fig. 4—Expansion data.

The nickel-chromium alloys and most of the chromium-nickel alloys are essentially austenitic alloys by reason of their high nickel content. Consequently they are more stable at high temperature than the straight chromium compositions. The effect of carbon in promoting brittleness is less apparent in the nickel-chromium alloys although excessive carbon content involves a serious loss in high temperature strength. For this reason nickel-chromium alloy castings are usually produced with a carbon content of 0.40-0.70%. Recommended design strength values for the two best known and widely used nickel-chromium alloys are shown in Fig. 2.

The design strength values given in Fig. 1 and 2 have been developed from data largely derived from service installations. Little is known concerning the mechanism of strain at elevated temperature and from data as yet derived it is not possible to assign infallible design strength values to the various commercial heat resisting

alloys of which those already discussed are representative. Obviously "design strength" must comprehend loss of section due to corrosion which in extreme cases may approximate 10% or more per year. Design strength should also provide a margin of safety in cases of accidental overloading or overheating which may occur in spite of the most advanced methods of control. Where corrosive conditions compel the use of an unstable alloy it must be considered that the rate at which transformations adversely affecting the strength of the material take place is a function of time as well as temperature and due allowance must be made for this phenomenon in arriving at a suitable design strength value for a given temperature.

Cases in which premature failure take place due to actual lack of load carrying capacity are fortunately rare. This is due to the circumstance that most heat resisting castings must be designed within practical foundry limitations which generally compel departure from theoretical ideals. But where no such limitation exists the most dependable practice is to employ design values which have been arrived at from accumulated data covering many thousand actual installations where load, temperature, and service life are definitely known and where the "coefficient of abuse" has been included in consideration of the service life.

Casting Design—It is always preferable to design a section of symmetrical proportions such as the I-beam, rectangle, or tube instead of channels, angles, and tees which are eccentric to at least one axis. H. Klouman in the Book of Stainless Steel, p. 637, points out that the eccentric shapes cannot be produced as straight castings due to the effect of unequal cooling in the mold, nor can such

sections be put into service after straightening with assurance that they will remain straight. Hollow, circular shapes are well produced as centrifugal castings which are now available in all heat resisting analyses. Centrifugal castings are less subject to residual stresses which are retained in tubular shapes that have contracted while in a plastic condition against a relatively unyielding sand core.

Metal thickness should be as uniform as possible because nonuniformity of integral parts tends to create shrinkage strains and cavities when cooling unequally from the molten state. Such sections are predisposed to warp in service due to different rates of change of temperature in the same casting. For similar reasons solid intersections should be avoided where possible. The effect of shrinkage can be minimized by the use of carefully located chills or preferably by coring through the mass of metal at intersections.

In designing structural elements it is important that the metal be correctly disposed. Trussed girders can frequently be designed more efficiently than solid webbed beams because the lightly stressed metal near the neutral axis of the latter can be used to greater advantage in truss chords and web members operating at full design stress. In operation trussed members permit freer circulation of heat than solid webs and thus have more even temperature distribution. Carefully placed brackets and ribs will often render a light lattice structure as stable as a heavy solid element because dead weight at high temperature is a large contributing factor creating stress which frequently exceeds that due to externally applied loads. Fig. 3 shows comparison of solid and trussed beams having the same load carrying capacity.

Where choice exists as to the size of individual castings it is preferable to use several short pieces instead of one long piece, thus facilitating the casting of lighter metal sections and minimizing the possibility of warpage due to unequal temperature distribution throughout the length of the longer member. Multiple spans designed as continuous beams are objectionable because supporting elements operating at high temperature are always subject to irregular displacements relative to each other and a slight displacement of supports seriously affects the magnitude of the stresses calculated on the assumption of continuity.

Thermal Expansion—In the design of heat resisting castings it is imperative to allow for free expansion of each part. Otherwise, stresses of incalculable magnitude may arise with the certainty of failure or distortion somewhere in the structure. The coefficient of expansion for all heat resisting alloys is not constant throughout a given temperature range but for practical purposes may be considered so. Fig. 4 gives average rates of expansion for the chromium-nickel and nickel-chromium alloys included in the preceding discussion.

Copper as an Alloying Element in Steel

By C. H. Lorig*

General—Most iron ores contain copper in small amounts which enter the iron on reduction. Copper from this source appeared in many of the early irons, their long life being attributed by some to its presence. Recently the relative cheapness of copper and its marked influence on properties of iron and steel have stimulated an interest in its use as an alloy. With several previous drawbacks to their use overcome through investigations, the commercial applications for steels containing copper have increased rapidly.

Constitution of Copper Steels—The constitution of the iron-copper alloys is given in another section of this Handbook.

The constitution of alloys from the iron-rich corner of the iron-copper-carbon system is quite uncertain, although Ishiwara, Yonekura and Ishigaki (Science Report, Sendai, ser. 1, vol. 15, 1926, p. 81-114), outlined a possible iron-copper-cementite diagram. In this diagram the solid phases existing are delta iron, gamma iron or austenite, alpha iron or ferrite, iron carbide or cementite, and epsilon, the copper-rich solid solution. The system did not have a closed gamma loop. Carbon decreased the solubility of copper in liquid iron, forming a two-liquid region, and decreased the solubility of copper in solid iron.

From lattice constant determinations, Norton found the maximum solubility of copper in alpha iron at 1560°F. to be 1.4%. The solubility falls rapidly with temperature down to 1200°F., where it remains constant at 0.35%. Because at room temperature the solubility of copper in iron is small, the epsilon phase may exist in all copper steels except in those containing only a few tenths per cent of copper. The actual existence of the epsilon phase in copper steels, however, is determined somewhat by the treatments given them.

Copper raises the A_1 point and depresses the A_3 and A_{cm} points in steels. It also retards the alpha-gamma transformation. The work of the Japanese investigators indicated that the eutectoid is located approximately at 0.9% carbon and 1.9% copper at a temperature of 1290°F.

The microstructure of steels containing only a small percentage of copper does not differ greatly from that of carbon steels. A new constituent to appear, the copper-rich solid-solution epsilon, forms either a network or large particles during solidification and cooling, or tiny particles, sometimes of submicroscopic dimensions, dispersed throughout the grains when precipitated from alpha iron. Under ordinary conditions the epsilon phase contains practically no carbon and little iron.

Alloying of Copper in Steel—In the reduction of cupriferous iron ores all of the copper enters the pig iron. On the basis of this, it was suggested that the introduction of copper in amounts required for the manufacture of corrosion resistant copper steels be effected by the use of copper bearing ore in the blast furnace.

Copper may be added to steel in the form of alloys, copper bearing pig iron, or steel scrap. A widely used practice is to introduce the copper in its metallic state, as ingots, borings, scrap, baled wire, or other shapes. It may be added to the steel in the furnace, in the ladle, or in the mold. Losses of copper during the making of a heat of steel are negligible.

Effect of Copper in Steel—General—No particular difficulties or peculiarities in the making of copper steels can be ascribed to the presence of copper. In the fabrication of the steels, however, hot working difficulties at high temperatures have been noted. As an alloying element, it affects the properties of steels, particularly the corrosion resistance, and mechanical, electrical, and magnetic properties.

Mechanical Properties—The changes in mechanical properties with carbon content of normalized and of water quenched and tempered steels containing 0, 1, and 2% copper are shown in Fig. 1 and 2. For normalized steels the changes in properties for a given copper content are practically independent of the carbon, while for water quenched and drawn steels the changes, for a given copper content, decrease with carbon.

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The Alloys of Iron Research Monograph, "The Alloys of Iron and Copper," by J. L. Gregg and B. N. Daniloff, McGraw-Hill Co., 1934, deals with this subject most comprehensively and, therefore, material from it was used freely in preparing this section.

For the first 0.5% copper the mechanical properties are but slightly affected, but as the copper content increases changes in properties are rapid. They reach a maximum at about 3% copper. The properties of normalized steels containing from 0.5-3.0% copper change linearly with copper content. With quenched and tempered, and annealed steels and steels tempered after normalizing rapid changes in properties occur when the copper increases from 0.5-1.2%, but further alloying with copper is appreciably less effective.

The yield strength rises with copper more rapidly than the tensile strength. For the low carbon steels it exceeds the tensile strength when the copper content approaches 3.0%.

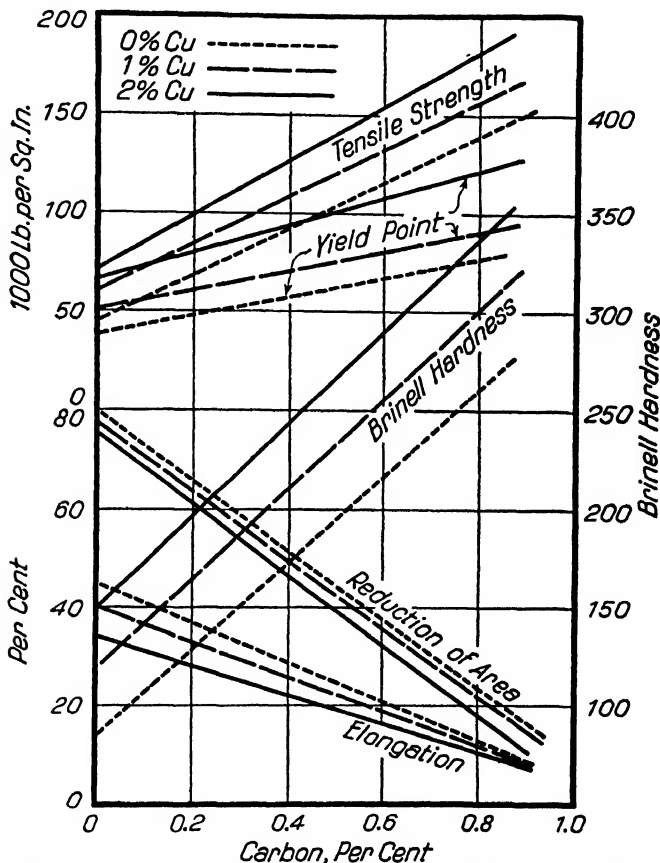


Fig. 1—The effect of carbon and copper on mechanical properties of steels containing 0, 1, and 2% copper after normalizing at 1650°F.

The ductility of carbon steels is lowered by copper. For a given strength, however, copper reduces the ductility less rapidly than carbon. This is shown in Fig. 3 where the Charpy impact and tensile strength values for normalized carbon and copper steels are plotted.

Test data on comparatively high carbon steel containing up to 1.65% copper indicate no change in the endurance ratio.

Scattered information on the properties of cold worked copper steels and on creep and high temperature tensile properties of copper steels indicate that improvements along these lines are produced by copper.

Heat Treatment—The alloying of copper to steels does not affect their response to heat treatment nor does it materially alter the heat treating schedules adopted for unalloyed steels. The reduction in the rate of the gamma-alpha transformation

by copper permits less drastic quenching and gives the steels greater depth hardening qualities. Slow cooling on annealing or prolonged drawing treatments cause the coalescence of the copper-rich epsilon phase in medium and high copper steels which may produce appreciable changes in the structure.

Steels containing more than 0.6% and up to about 4% copper are susceptible to precipitation hardening due to the decreased solubility of copper in ferrite from the lower critical temperature to a temperature of about 1110°F. Steels with from 1.2 to about 1.5% copper are most susceptible to precipitation hardening.

To produce the supersaturated solid solution of copper in ferrite which will respond to a precipitation hardening treatment, it is unnecessary to quench. In low carbon steels, rates of cooling greater than 2°C. (3.6°F.) per min. are sufficient for maximum hardening effects, while some hardening occurs even after cooling as slow as 0.4°C. (0.7°F.) per min.

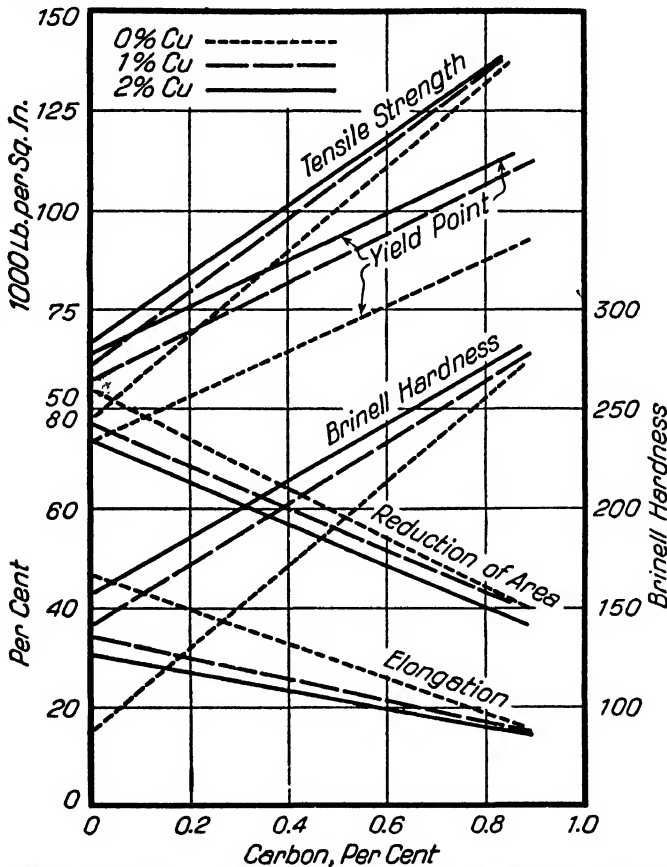


Fig. 2—The effect of carbon and copper on mechanical properties of steels containing 0, 1, and 2% copper after water quenching from 1650°F. and tempering at 1250°F.

Precipitation hardening is effected by reheating the supersaturated solid solution of copper in ferrite for a period of time, determined by the condition of the steel and the temperature, within the range of 750°-1245°F. The greatest hardness increase takes place on heating to from 840°-930°F. for from 3-20 hr.; the longer heating time being required for the lower temperature.

The maximum changes in mechanical properties resulting from precipitation hardening normalized carbon steels containing 1.5% copper are shown in Fig. 4. The tensile strength, yield strength and Brinell hardness increase; the reduction of area and elongation decrease on hardening, the effects diminishing as the carbon content of the steels increases.

Precipitation hardening in copper steels is seemingly unaffected by small quantities of many other alloying elements, but it is affected by cold working.

The precipitation of the copper increases the electric conductivity, the density, and the residual induction of the steels.

Physical Properties—The electric resistance of iron is increased with copper up to at least 0.62%. In steel the maximum resistance is attained at a copper content which is the lower, the higher the carbon content.

It is stated that magnetic properties of steels of the permanent magnet type are improved by copper. The decrease in magnetic flux on aging is somewhat smaller.

Case hardening of steels is not affected by copper, provided the surface is not oxidized and the copper content is below 3%.

Corrosion Resistance—The results of the A.S.T.M. atmospheric corrosion tests summarized by Kendall and Taylerson are given in Table I.

The atmospheric resistance of steel to corrosion increases rapidly up to 0.25% copper and then more slowly for higher percentages. The resistance to corrosion

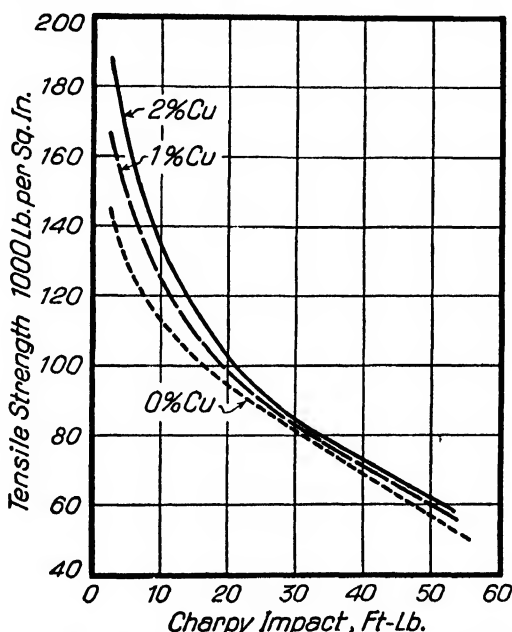


Fig. 3—The relation of tensile strength to Charpy impact resistance of normalized carbon steels containing 0, 1, and 2% copper.

continues to increase above 0.50% copper only if it is retained in solid solution in the ferrite. This is shown by weight losses of copper-bearing steel sheets exposed to sea air for 10 months. They are as follows:

No.	C, %	Cu, %	Weight Loss, g./sq.cm.	Treatment
1	0.041	0.018	0.01671	Box annealed
2	0.017	0.196	0.01495	Box annealed
3	0.023	0.492	0.01445	Box annealed
4	0.020	1.02	0.01563	Box annealed
5	0.020	1.02	0.01360	Box annealed; reheated to 1435°F.; air quenched.

The differences in loss of weight of specimens 4 and 5 imply that the atmospheric corrosion in the higher copper steels is accelerated only when the copper exists out of solid solution in the ferrite.

Numerous exposure tests have indicated that painted and galvanized surfaces are more durable on copper-bearing than on noncopper-bearing steels.

While it is definitely established that copper increases the resistance of iron and steel to atmospheric corrosion, the results of submerged corrosion tests are not in good agreement. The influence of copper under the latter conditions is secondary to and is masked by variations in external conditions such as oxygen concentration, mill scale, and location of tests.

In summarizing the U. S. Bureau of Standards soil corrosion investigation, Logan stated that copper bearing steel does not appear to be superior when buried in soil, perhaps because of the limited supply of oxygen.

Hot Working Properties—The reputed hot shortness in the low and medium copper containing steels does not exist. Although cracks appear on the edge and surface of steels containing as little as 0.20% copper during forging or hot rolling above 2000°F., they are caused by the intergranular penetration of copper deposited beneath the scale of copper steels. This intergranular penetration of copper and the surface cracking may be corrected by adding small amounts of nickel, by hot working below the melting temperature of the copper-rich solid solution, or by preventing the formation of scale on the steel.

The high copper steels, on the other hand, owing to the occurrence of intergranular copper-rich solid solution, may be distinctly hot short at high hot working temperatures.

Table I
Summarized Results of the A.S.T.M. Atmospheric Corrosion Tests

Location of Test	Duration of Test		Gage No.	Material		Failures to Date	
	Begun	Finished		Kind	No. of Sheets	No.	Per-centage
Pittsburgh, Pa. (Industrial)	Dec., 1916	March, 1923	22	Copper	146	123	84.4
				Noncopper	84	84	100.0
				Total	230	207	90.0
			16	Copper	132	None	0.0
				Noncopper	126	102	81.0
				Total	258	102	39.5
Fort Sheridan, Ill (Rural)	April, 1917	April, 1928	22	Copper	136	50	36.8
				Noncopper	83	77	92.8
				Total	219	127	58.0
			16	Copper	136	None	0.0
				Noncopper	124	4	3.2
				Total	260	4	1.5
Annapolis, Md (Marine)	Oct., 1916	Last inspection April, 1933	22	Copper	148	4	2.7
				Noncopper	79	44	55.7
				Total	227	48	21.1
			16	Copper	130	None	0.0
				Noncopper	129	None	0.0
				Total	259	None	0.0

Weldability—The welding qualities of steels are not influenced by copper in amounts at least up to 0.75%. The metal deposited in the weld may be strengthened by copper.

Commercial Copper Steels—The bulk of the tonnage of copper steels falls in the group containing only a few tenths per cent copper, it being added to enhance the corrosion resistance.

There is, however, a rapidly increasing tonnage of wrought steels being made containing from about 0.3% to several per cent copper, the copper being added to effect specific changes in mechanical and physical properties other than corrosion resistance. A high strength, cheap structural steel was developed in Germany containing from 0.12-0.25% carbon, 0.3-0.5% silicon, 0.5-1.0% copper, and 0.4-0.6%

chromium. Another copper-chromium structural steel developed in England contains 0.3% carbon, 0.7-1.1% manganese, 0.7-1.1% chromium, and 0.25-0.50% copper.

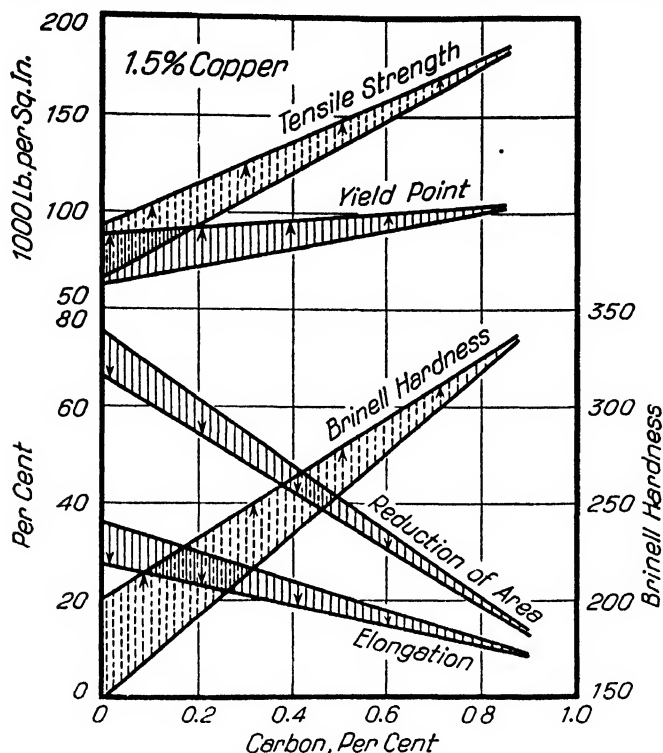


Fig. 4—The changes in properties of normalized carbon steels containing 1.5% copper on precipitation hardening. The width of the bands and the direction of the arrows represent the maximum changes in properties on precipitation hardening and direction which these changes take with respect to properties of normalized steels.

Table II
Mechanical Properties of Cast Steels Containing Copper

Cu., %	Heat Treatment	Tensile Strength, psi.	Yield Strength, psi.	Elongation in 2 in., %	Reduction of Area, %	Brinell Hardness	Charpy Impact, Ft.-lb.
0	Normalized 1 hr. 1650°F.	85,500	54,500	29.5	53.4	146	21.1
1.21		97,500	68,000	25.5	51.0	170	17.2
1.76		114,500	86,000	19.8	42.0	216	11.1
2.40		121,000	91,500	16.8	34.7	229	6.9
0	1 hr. at 1650°F.; water quenched; tempered 1 hr. at 1200°F.	92,500	66,500	26.0	61.8	164	32.4
1.21		104,500	89,000	20.5	55.6	198	25.9
1.76		113,000	99,000	18.8	46.9	216	20.6
2.40		116,500	105,000	20.0	52.3	222	21.6
0	Fully annealed after 1 hr. at 1650°F.	77,000	43,500	28.7	44.5	134	13.8
1.21		90,000	61,000	24.8	43.6	161	11.8
1.76		90,500	58,500	24.5	41.4	159	10.1
2.40		89,500	58,500	24.5	44.9	157	12.1
0	Normalized 1 hr. 1650°F.; precipita- tion hardened 3 hrs. at 930°F.	83,500	53,000	29.3	51.9	146	20.3
1.21		110,500	82,500	21.0	45.8	201	11.6
1.76		116,500	89,500	18.8	38.8	215	10.1
2.40		119,000	93,500	19.3	44.2	223	9.3

Both steels have higher yield strengths than carbon steels of the same carbon contents and ductilities not appreciably lower than those of the carbon steels. A high

strength, corrosion resistant steel containing 0.10% carbon, 0.10-0.30% manganese, 0.10-0.20% phosphorus, from 0.50-1.0% silicon, 0.30-0.50% copper, and 0.50-1.50% chromium, recently developed here, is being used in the construction of light weight transportation equipment.

Other recently developed copper-bearing steels of the low alloy, high strength type, are as follows:

% C	% Mn	% Cu	% Ni	% Mo	% Si	% P	% Cr
0.08-0.22	.....	1.00	2.00	.....	.....	.....	.....
0.12 max.	1.00 max.	0.5-1.5	0.5-1.0	0.20	.....	.....	.....
0.12 max.	0.5-0.7	0.9-1.25	0.45-0.65	.....	0.30 max.	0.10-0.15	.....
0.12 max.	0.15-0.90	0.30-0.80	0.30-0.80	0.05-0.25	.....	0.05-0.15	.....
0.25 max.	0.75 max.	0.30-0.50	0.25 max.	.....	.....	0.08-0.10	.....
0.35 max.	1.25-1.75	0.40 min.	.....	.....	0.30 max.	.....	0.25 max.
0.14	0.70-0.90	0.25-0.30	.....	.....	0.15-0.20	.....	0.12
0.08-0.30	0.60-0.70	0.40-0.60	0.25 max.	.....	0.50 max.	.....	0.25 max.

The presence of 1 or 2% copper in corrosion resistant chromium steels increases the resistance to atmospheric and salt water corrosion and to attack by certain acids. The influence, however, is not great and few of the corrosion resistant steels contain copper. A ferritic steel for resistance to atmospheric corrosion contains approximately 16% chromium, 1% silicon, 1% copper, 0.40% manganese, and under 0.1% carbon. Another for abrasion resistance contains 0.3% carbon, 20% chromium, and 1% copper. Several austenitic corrosion resistant alloys recently developed contain from 1-4% copper.

Many cast steels are alloyed with copper. The mechanical properties of steels with 0, 1.21, 1.76, and 2.40% copper and with base compositions of 0.31% carbon, 0.42% silicon, 0.75% manganese, 0.029% sulphur, and 0.034% phosphorus are given in Table II.

A heat treated cast steel crankshaft containing 1.25-1.40% carbon, 0.50-0.60% manganese, 1.90-2.10% silicon, 0.35-0.40% chromium, 2.50-2.75% copper, and 0.10% (max.) phosphorus is being used in one make of automobile.

Manganese As An Alloying Element in Pearlitic Steels

By A. Oram Fulton*

Manganese is a very hard grayish white metal, with a reddish lustre. It takes a high polish and is not malleable. When in an extremely pure state, manganese scratches glass. The article "Physical Constants of the Principal Alloy Forming Elements" in this Handbook gives the physical constants for manganese.

Historical—Manganese was first isolated in 1774 by Gahn working with Scheele. It was used as an addition to crucible steel by Heath in 1839. Mushet in 1856 patented the addition of spiegel to Bessemer steel. Mushet also developed the first so-called "high-speed" steels which contained about 2.5% manganese.

Sir Robert A. Hadfield in 1882 made a series of steels containing from 0.83-21.69% manganese. The experiments and conclusions drawn were detailed in a paper which he presented before the British Iron and Steel Institute in 1888.¹

Hadfield's conclusions resulted in a decided impetus being given to the manufacture and use of austenitic high manganese steels, but steel containing manganese in low percentages or pearlitic manganese steels were condemned as being brittle and having no practical applications.

In the light of later developments, we now know that this erroneous conclusion with regard to low manganese steels was due to the fact that Hadfield did not work

with a sufficient variety of low carbon, low manganese steels, or rather, with low manganese steels containing carbon in the proper relation to the manganese content.

In 1903 Leon Guillet reported² an extensive research on manganese steels. He examined two series of steels: First, the steels containing a small percentage of carbon (at the most 0.3%); second, the steels in the vicinity of the eutectoid ratio containing from 0.7-1% carbon.

The result of Guillet's experiments was to completely disprove the previously accepted theory that low manganese steels were brittle. Indeed Guillet went farther and added that "these steels possess a remarkable shock resistance, and especially a uniformity which is only met with exceptionally in carbon steels."

Following Guillet's experiments low manganese steels began to be manufactured commercially in this country and have had a steady development to the point where they are now meeting with exceeding favor by reason of their machinability, case hardening properties, strength and toughness.

Ores and Their Occurrence—Manganese ores are found in many parts of the world. Their occurrence in the United States may be grouped as follows:

1. Manganese ores, containing at least 35% manganese, are found most abundantly in the Appalachian and Piedmont regions of Virginia and Georgia, and on the Pacific Coast.

2. Manganiferous-iron ores, containing usually more than 5% manganese and a variable proportion of iron, are found chiefly in New England, the Appalachian region, and the Lake Superior iron district.

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¹R. A. Hadfield, *On Manganese Steel*, J. Iron Steel Inst., 1888, v. 2, p. 70.

²L. Guillet, *Recherches sur les Aciers au Manganèse*, Génie civil, 1903, v. 43, p. 261, 280; and L. Guillet, *Sur les Propriétés et la Constitution des Aciers au Manganèse*, Compt. rend, 1903, v. 137 p. 480.

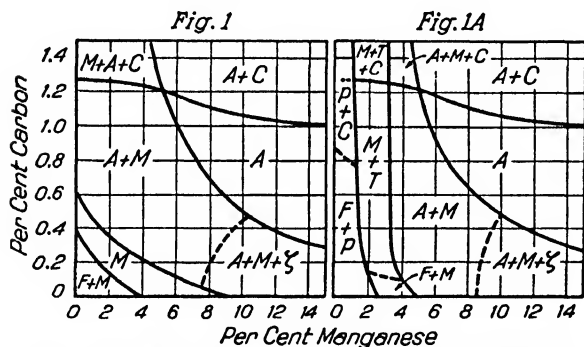


Fig. 1—Extra equilibrium constitution chart for condition resulting from water quench from 1740°F.

Fig. 1A—Same as Fig. 1, but free air cooled from 1740°F.

3. Manganiferous-silver ores, consisting of mixtures of manganese, iron oxides, and hydroxides with small amounts of lead and silver, are found in the Rocky Mountain and Great Basin regions, but chiefly at Leadville, Colo.

Enormous deposits of manganese ore are found in Southern Russia and Minas Geraes, Brazil.

Manganese itself has no uses but forms valuable alloys with copper, iron, zinc, tin, aluminum, lead, and magnesium. Those with iron, depending upon the percentage of manganese content, are known variously by the names spiegeleisen, ferromanganese, and silicomanganese.

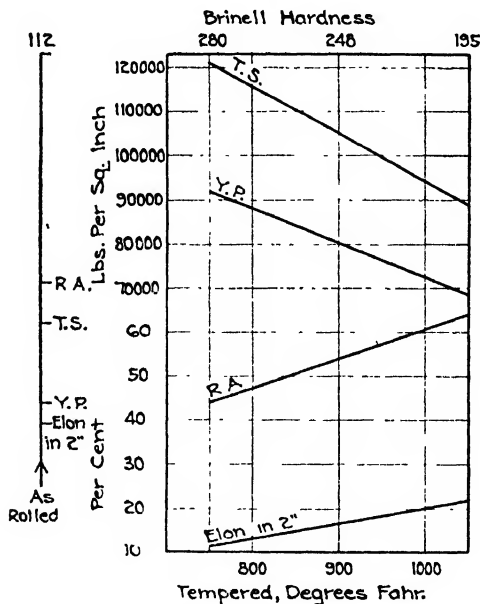
Method of Adding Manganese to Steel^a

Standard Ferromanganese—Manganese is most commonly introduced into steel in the form of ferromanganese which analyzes approximately: Manganese 78-82%, iron 15-19%, carbon 6-8%, with small percentages of silicon, phosphorus, and sulphur. Frequently, in order to lower costs, ferromanganese is added in the ladle, but a much better quality of steel is produced when the ferromanganese is added in the furnace. The latter method, however, results in a greater loss of manganese.

Low Carbon Ferromanganese—In making low carbon, low manganese steel, standard ferromanganese of the above analysis, because of its carbon content, cannot be used entirely, and must be supplemented by the use of a low carbon ferromanganese. For this purpose a low carbon ferromanganese (carbon 0.3-1%, manganese 80-85%) is used, which can be added either in the ladle or furnace, preferably in the furnace.

Spiegeleisen—Spiegeleisen, which in effect is a high manganese pig iron, containing 15-30% manganese and 4.5-5% carbon, is used in Bessemer and basic open hearth practice in making high carbon steels, usually being added to the steel in molten form direct from a cupola.

Fig. 2—Physical properties of manganese steels, Type 2, Table I. Bar $\frac{3}{4}$ in. round. Quenched into water from 1650°F.



Silicomanganese—Frequently in making low carbon steel where there is no objection to silicon, silicomanganese is used. Silicomanganese analyzes: Manganese 65-70%, silicon 16-25%, and carbon either 1, 2 or 2.5% maximum as desired. It is added either in the ladle or the furnace, preferably the latter.

Effect of Manganese on Steel—Manganese when added to steel has a beneficial effect both directly and indirectly. It increases the strength of the steel directly in that the excess manganese combines with some of the carbon to form the carbide of manganese, Mn_3C , and this carbide is found associated with the iron carbide, Fe_3C , in cementite.

It has generally been held that iron and manganese form a series of solid solutions. In the light of recent research it appears that such is not the case. The solubility of manganese in iron at room temperature seems to be close to 1.6% manganese. If more than that amount is added to iron (or to steels very low in carbon) iron and manganese often display martensitic-like structures, which on exam-

^aW. J. Priestly, *Metals and Ferroalloys Used in the Manufacture of Steel*, Metals Handbook.

ination prove to be two kinds of solid solutions. In this respect iron-manganese alloys appear to be much like the alloys of iron and nickel.⁴

The indirect beneficial effect of adding manganese to steel is due to its action as a scavenger. It counteracts the effect of certain harmful oxides or gases and eliminates the harmful effect of sulphur by combining readily with it to form manganese sulphide, MnS .

The addition of manganese to steel lowers the transformation temperatures. A summary⁵ of published results obtained in studies of pearlitic manganese steels showed that the A_{c1} point is lowered $11^{\circ}F.$ for each per cent increase in manganese; the A_{c2} point is lowered $116^{\circ}F.$ for each per cent increase in manganese up to 1%, but only $6-11^{\circ}F.$ for each per cent increase in manganese up to 3%; the A_{r1} point is lowered $125^{\circ}F.$ for each per cent increase in manganese; the A_{r2} point is lowered

variably, but about $90^{\circ}F.$ for each per cent increase in manganese.

Manganese not only lowers the transformation points, but renders such transformation extremely sluggish. That is to say, the allotropic transformation does not take place at any definite temperature, but occupies a whole range of temperatures, sometimes as much as 150° . In simpler words, it may be explained that the beginning and the end of the transformation are about 150° apart, this figure depending on the amount of manganese.⁶

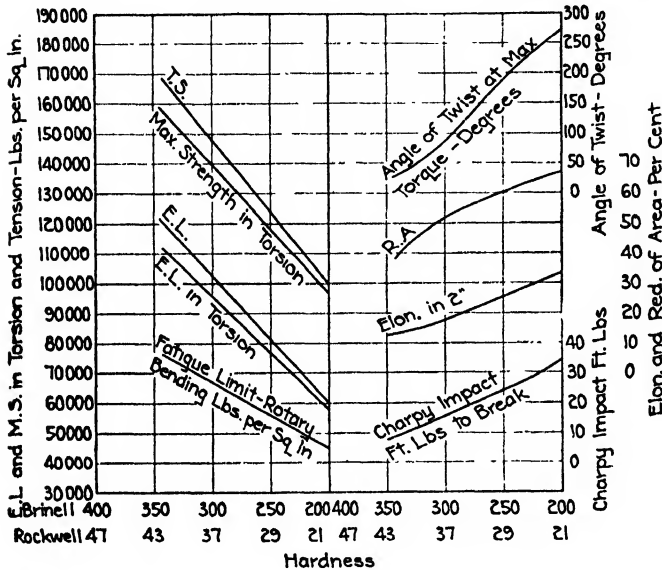


Fig. 3—Physical properties of manganese steel, Type 3, Table 1. The Rockwell "C" scale was used. Quenched into water from $1575-1600^{\circ}F.$ and tempered to the hardness shown.

In a study of 36 iron-carbon-manganese alloys of commercial purity limited by 1.5% carbon and 15% manganese, by E. C. Bain, E. S. Davenport, and W. S. N. Waring in a paper presented to the A.I.M.E. in Feb., 1932, the extra equilibrium constitution chart was developed for the condition resulting from water quench from $1740^{\circ}F.$, also, for the condition resulting from free air cool from $1740^{\circ}F.$ These charts are presented in Fig. 1 and 1A.

The letters used in the diagrams represent the following constituents: A, austenite; F, ferrite; C, carbide; ϵ , epsilon; M, martensite; T, troostite; P, pearlite.

Standard Manganese Steels—Table I lists the pearlitic manganese steels which are most commonly used. There are other analyses adopted by individual manufacturers and users, but the following are those having at present general distribution.

⁴Vsevolod N. Krivobok, Personal Communication.

⁵J. Straus, Medium Carbon Pearlitic Manganese Steels, Trans., A.S.S.T., 1928, v. 14, p. 2, 3.

⁶Vsevolod N. Krivobok, Personal Communication.

In the case of the steels with S.A.E. designations the term "standard" refers to the analysis range recommended by the Society of Automotive Engineers. In the case of steels without S.A.E. nomenclature the term "standard" refers to recommended analyses of individual manufacturers and users.

Table I
Composition Pearlitic Manganese Steels

Steel Type	S.A.E. No.	C	Mn	P	S
1	X-1314	0.10-0.20	1.00-1.30	0.045 max.	0.075-0.15
2	X-1315	0.10-0.20	1.30-1.60	0.045 max.	0.075-0.15
3*	.....	0.10-0.20	1.30-1.60	0.04 max.	0.08 max.
4	X-1330	0.25-0.35	1.35-1.65	0.045 max.	0.075-0.15
5	X-1335	0.30-0.40	1.35-1.65	0.045 max.	0.075-0.15
6	X-1340	0.35-0.45	1.35-1.65	0.045 max.	0.075-0.15
7	T-1330	0.25-0.35	1.60-1.90	0.040 max.	0.050 max.
8	T-1335	0.30-0.40	1.60-1.90	0.040 max.	0.050 max.
9	T-1340	0.35-0.45	1.60-1.90	0.040 max.	0.050 max.
10	T-1345	0.40-0.50	1.60-1.90	0.040 max.	0.050 max.
11	T-1350	0.45-0.55	1.60-1.90	0.040 max.	0.050 max.
12*	.....	0.45-0.55	1.00-1.30	0.040 max.	0.08 max.

*Types 3 and 12 are frequently furnished with additions of chromium and/or molybdenum in varying percentages.

Types 1, 4, and 3 are most commonly used for case hardened parts, such as roller bearings, camshafts, and gears. These steels harden with a hard case at low temperatures and possess a strong, tough core. They all possess superior machining qualities and are classed as free cutting steels.

Case Hardening Types 1, 2, and 3—Following are the various recommended practices for case hardening of these grades:

X-1314—I and X-1315—I

1. Carburize at 1650-1700°F.
2. Quench direct
3. Temper to 250-325°F.

X-1314—II and X-1315—II

1. Carburize at 1650-1700°F.
2. Quench direct
3. Reheat to 1400-1450°F.
4. Quench
5. Temper to 250-325°F.

X-1314—III and X-1315—III

1. Carburize at 1650-1700°F.
2. Cool slowly or in box
3. Reheat to 1400-1450°F.
4. Quench
5. Temper to 250-325°F.

X-1314—IV and X-1315—IV

1. Carburize at 1650-1700°F.
2. Cool slowly or in box
3. Reheat to 1650-1700°F.
4. Quench
5. Reheat to 1400-1450°F.
6. Quench
7. Temper to 250-325°F.

X-1314—V and X-1315—V

1. Heat to 1500-1650°F. in cyanide or activated bath
2. Quench in oil or water
3. Temper if desired

Parts "cased" in activated baths may be given refining heats as indicated in preceding heat treatments.

The particular practice selected in a specific instance depends upon a variety of factors, as, for instance, the degree of core toughness, the depth of case, the hardness of case desired, the relative importance of the part, and the cost of the operation.

The allotropic transformation in pearlitic manganese steels occupies a whole range of temperatures, sometimes as much as 150° apart. This means that these steels are sluggish in passing through the critical range. It is desirable to keep the double carbides of iron and manganese in solid solution in order to prevent brittleness. With Types 1, 2, and 3 this can be done best by quenching them direct from the pot rather than to permit the carbides to be precipitated from solid solution by cooling in the pot. When this direct quench from the pot is used, it should, of course, be followed by subsequent treatment for the refinement of the case.

Heat Treatment and Uses of Pearlitic Manganese Steels—Types 1, 2, and 3 are frequently heat treated for strength and toughness by direct quench in water without carburizing and then reheating as required. Excellent physical properties result. Fig. 2 and 3 show the physical properties of two of these steels with varying tempering temperatures or at different conditions of hardness obtained by varying heat treatments.

Types 4, 5, and 6 are classified as free cutting steels and for many purposes may be substituted for carbon steels of similar carbon content where improved machining, deeper hardening, and higher physical properties are desired. With increasing carbon, the manganese steels become primarily oil hardening and can be treated in water only by exercising great care and extreme risk of cracking.

X-1330—I

1. Heat to 1525-1575°F.
2. Quench in water or oil depending upon section
3. Temper to required hardness

X-1330—II

1. Normalize at 1650-1750°F.
2. Machine
3. Heat to 1525-1575°F.
4. Quench in water or oil depending upon section
5. Temper to required hardness

Heat Treatments**X-1335—I and X-1340—I**

1. Heat to 1500-1550°F.
2. Quench in water or oil depending upon section
3. Temper to required hardness

X-1335—II and X-1340—II

1. Normalize at 1650-1750°F.
2. Machine
3. Heat to 1500-1550°F.
4. Quench in water or oil depending upon section
5. Temper to required hardness

Types 7, 8, 9, 10, and 11 are manganese alloy steels and for many applications may be used interchangeably with other medium alloy steels of similar carbon content. They possess good physical properties and may frequently be used in place of other medium alloy steels at a saving in cost. These steels are primarily intended for oil hardening and can only be quenched in water at extreme risk. Common uses are heat treated shafts, gears, and spindles.

Steel Type 12, with additions of chromium or molybdenum, or both, is used

where high physical properties are required. Common uses are gears, shafts, clutches, and bolts. This type is invariably quenched into oil. The physical properties of this steel are shown in Fig. 6 when heat treated to the varying degrees of hardness indicated in the abscissae.

The heat treatment consists of quenching into oil from 1475-1500°F. followed by tempering to the hardness desired.

General Properties of Pearlitic Manganese Steels

Welding—These steels cannot properly be classed as "welding steels," but may be used without difficulty in the manufacture of parts which involve welding in their fabrication.

Forging—None of these steels present any unusual difficulties in any of the regular forging operations, and can be freely used in parts which require forging as a necessary preliminary to their manufacture.

Cold Drawing—Pearlitic manganese steels may be cold drawn without difficulty. Like other alloy steels, it is recommended when cold drawing steels of 0.35% carbon or more that they be annealed so as to obtain a lamellar pearlitic structure before the drawing operation.

Machining—As a class, the pearlitic manganese steels are particularly free machining.

Indeed, the low carbon steels, such as Types 1, 2, and 3 in Table I are practically equivalent in their machining properties to Bessemer screw stock. As the carbon, manganese, and any other alloying elements are increased, the machining becomes more difficult. In the case of steels of over 0.40% carbon, it is recommended that they be annealed before machining.

Other Types of Manganese Steels—Pearlitic manganese steels are made with the manganese content higher (up to 3%) than those steels described above, but have a limited and special use. Steels are made containing manganese from 1-2% in combination of varying percentages with nickel, chromium, molybdenum, silicon, and other elements. These steels likewise are limited in use and have a highly specialized application. While they possess unusually good physical properties, they have presented too many manufacturing difficulties to the user for general adoption.

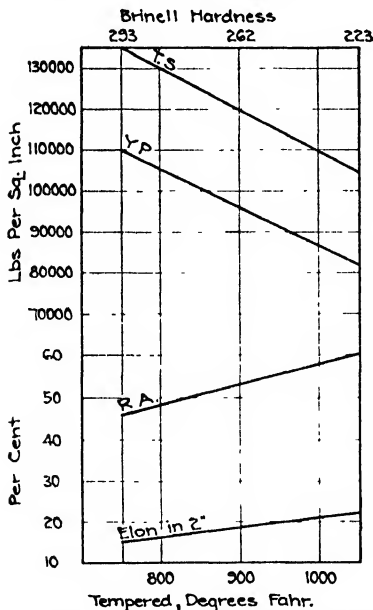


Fig. 4—Physical properties of manganese steel, Type 4, Table I. Bar $\frac{1}{2}$ in. round. Quenched into oil from 1525°F.

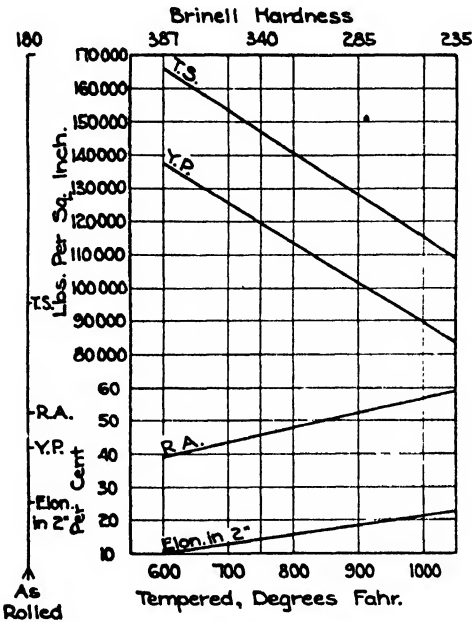


Fig. 5—Physical properties of manganese steel, Type 5, Table I. Bar $\frac{3}{4}$ in. round. Quenched into oil from 1475°F.

The chief difficulties are that they add considerable cost in fabrication due to difficulty in the forging and machining operations.

Manganese in Tool Steel—The average "normal" manganese content in tool steel is 0.20-0.35%. One special type of manganese tool steel has very decided nonchangeable or non-deforming qualities, however, and is very generally used. The composition of this steel varies somewhat with different manufacturers. The approximate chemical composition is C 0.90-1.00% and Mn 1.00-1.50%.

Some manufacturers run the manganese as high as 1.80%, with or without vanadium, while others add 0.50% chromium, 0.50% tungsten, or about 0.25% vanadium, or combinations of these. This steel, however, depends essentially for its qualities upon the carbon and manganese content.

The heat treatment consists in quenching in oil from approximately 1450°F. followed by tempering as required, usually 325-400°F.

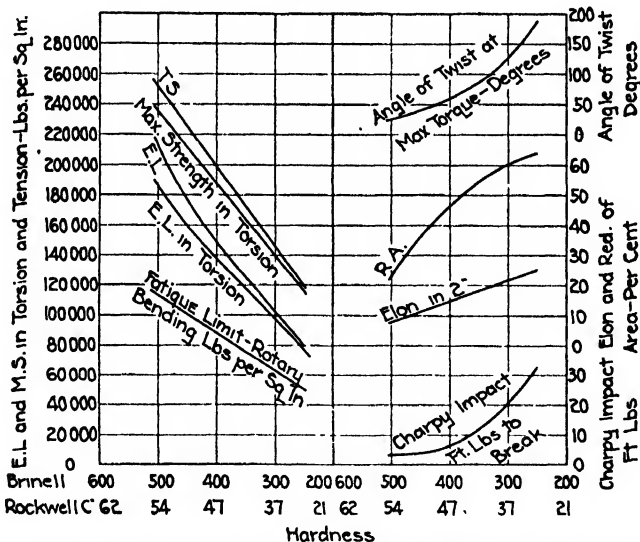


Fig. 6—Physical properties of manganese steel, Type 12, Table I, with Cr 0.55% and Mo 0.15%. Quenched into oil from 1475-1500°F. and tempered to the hardness shown.

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- S. Epstein and H. S. Rawdon, Steel for Case Hardening—Normal and Abnormal Steel, Bur. Standards, J. of Res., 1928, Sept., p. 440.
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Austenitic Manganese Steels

By John Howe Hall*

General—Austenitic, or Hadfield's manganese steel, was one of the first alloy steels discovered and produced on a commercial scale. The experiments of Sir Robert A. Hadfield at his father's Sheffield plant in 1882 led to the development of this alloy, which has occupied a unique place among metallurgical products for fifty years. In general, wherever hard materials are to be dug, crushed, handled, or moved, manganese steel parts are widely employed to resist the heavy wear involved in these operations, and so far no other metal has proved equal to it in a countless number of such applications.

Composition—The constitution of iron-manganese-carbon alloys is fully discussed on page 408 Metals Handbook. The useful range of composition for austenitic manganese steels does not include all the possible compositions shown in the constitution diagram of manganese steels. The valuable austenitic manganese steels are confined to those that are truly austenitic after quenching the steel in water from a temperature of 1830°F., or slightly over. This range of composition is that included between the line X—Y and W—Z in Fig. 1. The equations of these lines are approximately as follows:

$$\text{Carbon} = 1.075 + \frac{0.1 \text{ Mn}}{3} \quad \text{and}$$

$$\text{Carbon} = 1.075 - 0.04 \text{ Mn}^\dagger$$

To the right of the line WZ the steel in the quenched condition will contain considerable free carbide which reduces its strength and toughness. To the left of the line XY lie the steels that are more or less martensitic and brittle after quenching. This useful area was determined by an investigation made by the author in 1907-1908 in which a number of melts of steel were prepared, analyzed, and examined.

As not all the steels lying in the area bounded by these lines are sufficiently strong and tough for the severe service to which manganese steel is subjected, the composition (in %) of commercial austenitic manganese steels lies within the following limits:

C 1.00-1.40, Mn 10.00 (min.), Si 0.30-1.00, S 0.05 (max.), and P 0.10 (max.).

The more experienced makers set a lower limit of manganese at 11.00 instead of 10.00%, as the steels containing less than 11.00% manganese are somewhat lacking in toughness and strength.

Manufacture—The steel is made by the electric furnace, open hearth, or Bessemer process. In the case of the open hearth, Bessemer, and acid electric furnace methods, standard 80% ferromanganese is melted in crucibles, a cupola, or a small electric furnace, and is mixed in the ladle with approx. 5 times its weight of molten, low carbon steel. The latter may be tapped from an acid or basic open hearth furnace, a side-blown or small bottom-blown Bessemer converter, or an acid electric furnace. The cupola for the ferromanganese and the small converter for the low carbon steel are the preferred melting mediums for this method of manufacture. On

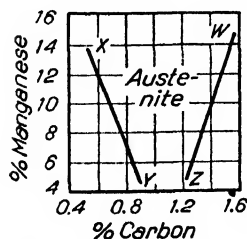


Fig. 1—Modified form of Guillet's diagram for manganese steels.

account of the difficulty of controlling the slag volume and composition, the cutting of the bottom, and the impossibility of keeping the loss of manganese within reasonable limits, it is not possible to add ferromanganese or manganese steel scrap to the bath in the acid electric furnace, as is done with most other alloy steels. For this reason, when the acid electric furnace is used as the melting medium, manganese steel scrap can not be remelted as a part of the charge, but must be disposed of in some other manner. When the open hearth furnace is the source of the metal, manganese steel scrap can be remelted in it, but only at the cost of the loss of practically all the manganese contained in the scrap.

Obviously, if converters are used to produce the steel base for the alloy, it is necessary to premelt the ferromanganese, as such a large amount of the latter cannot otherwise be incorporated

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†John Howe Hall, J. Ind. and Eng. Chem., 1915, v. 7, No. 2, p. 94.

in the steel without chilling it too much. Premelted ferromanganese is desirable also for mixing with open hearth steel, because, if the ferromanganese were added solid to the bath in the furnace, the loss of manganese would be excessive.

When the basic electric furnace is used, the ferromanganese is added in the furnace to a charge of low carbon steel, and more or less austenitic manganese steel scrap is generally incorporated in the charge. In some shops, all of the ferromanganese is added after the bath is melted, in others a large proportion of it is included in the initial charge. This is the only steel making process by which manganese steel scrap can be remelted without almost total loss of the contained manganese. The electric furnaces used are generally of the arc type, but of late years the coreless induction furnace has come forward as a competitor in this field.

The carbon content of standard 80% ferromanganese is such that, when the proper amount is added to a bath of low carbon steel, the manganese will be within the desired limits, and the carbon will be from 1-1.40%. If the carbon is below 1%, the steel is less resistant to wear. Carbon above 1.40% is undesirable, as it increases the tendency of the steel to crack in heat treatment.

Ferromanganese ordinarily carries enough silicon to give the resultant steel at least 0.30% silicon. No appreciable effect on the physical properties can be found from variations in silicon between 0.30 and 1%. When manganese steel is made in the basic electric furnace, with manganese steel scrap as a considerable proportion of the charge, it is desirable to add more silicon than is contained in the ferromanganese. In this case, a silicon content of over 0.50% in the finished steel is desirable.

The sulphur is usually so low as to be negligible, because the manganese forms MnS with part of the sulphur present in the steel, which floats to the surface and enters the slag.

The phosphorus content is dependent upon that of the ferromanganese used. It is generally between 0.06 and 0.09%. Up to 0.1% phosphorus may be present in the steel without ascertainable harmful effect.

Heat Treatment—In the cast condition, manganese steel is quite brittle. In this condition the structure consists of austenite, with considerable free carbide in patches and in a network between the austenite crystals. To strengthen and toughen the metal, the pieces are heated to between 1830 and 1940°F. and quenched in cold water. When the composition of the steel is within the correct limits, this treatment results in all the carbide being taken into solid solution in the austenite and produces a uniform austenitic structure and a high degree of strength and toughness. When the carbon exceeds 1.40-1.50%, free cementite will be found in amounts which increase in proportion to the carbon content and which will decrease the toughness and strength of the steel. A similar effect is caused in steel of correct composition if it is heated to too low a temperature before quenching, or if it is allowed to cool off too much between the time it is taken from the furnace and the time when it is immersed in the water.

If the heat treated steel were to be reheated for a long time at 660°F., or for a shorter time at or above 750°F., it would become exceedingly brittle, due to the liberation of carbide and the partial transformation of the austenite. This makes it impossible to reheat the steel after quenching for the removal of cooling stresses, as is done with most quenched steels. These stresses are far higher than in the case of most other steels, because the heat conductivity of manganese steel is but $\frac{1}{4}$ that of iron, and its coefficient of thermal expansion is somewhat higher—about $1\frac{1}{2}$ times that of pure iron. The low thermal conductivity results in a great difference in the cooling rate between light and heavy sections, and between the inside and the outside portions of heavy sections. When the castings are quenched, great stress is produced, which is still further increased by the high coefficient of thermal expansion. As tempering is not possible to relieve these stresses, reasonable uniformity of sections between different parts of a single casting is absolutely essential to avoid severe warping and even breaking of the castings in treatment.

The same considerations limit sharply the maximum thickness of manganese steel parts that can be successfully heat treated. When attempts are made to quench sections over 5 or at the very most 6 in. thick, the stresses due to the unequal cooling rates of the inside and the outside portions of the piece are so severe as to produce cracks, and these cracks generally begin at the center of the section and extend outward. As they do not always extend to the surface, their

presence is not always detected, with the result that the piece fails in service after a comparatively short life.

Properties of Austenitic Manganese Steel—In the rolled or hammered condition the properties of heat treated austenitic, high manganese steel will usually come within the following limits:

Tensile Strength, psi.	Limit of Prop. ¹ psi.	Elongation, % in 2 in.	Reduction of Area, %	Brinell Hardness
130,000-160,000	40,000-60,000	60-70	40-60	230

¹Limit of proportionality is given because austenitic manganese steels show no well marked yield point.

In the cast condition the properties of the heat treated steel vary somewhat, depending upon the form of the specimen from which the test piece is obtained. When a tensile bar is cast approximately to size, the properties obtained from it, which undoubtedly represent those of the cross section of similar light castings, are not so high as those of pieces ground from the usual coupons used to make tests of cast steels. The latter, of course, are fairly representative of the metal in the greater part of the cross section of heavier castings.

The temperature at which manganese steel is poured has a marked effect upon the strength of the castings. A high pouring temperature produces a coarse crystalline structure which is not refined in heat treatment, and which is some 15,000-20,000 psi. lower in tensile strength than the fine grained steel obtained when it is poured at lower temperatures. Depending upon pouring temperature and the origin of the test piece, the physical properties of cast heat treated austenitic manganese steel are as follows:

Type of Specimen	Tensile Strength, psi.	Proportional Limit, psi.	Elongation, % in 2 in.
Cast to size.....	80,000-110,000	.....	15-35
Ground from coupon.....	118,000 ^a	42,900 ^b	44.1 ^a

^aAverage of 15 tests.
^bAverage of 5 tests.

Type of Specimen	Reduction of Area, %	Brinell Hardness	Bend ½ in. x ¾ in. on 1 in. Pin, Degrees	Limit of Propor- tionality in Compression, psi.
Cast to size.....	15-35	180-220	180	.....
Ground from coupon.....	39.0 ^a	.....	...	24,000

^aAverage of 15 tests.

Type of Specimen	Shearing Strength, Single Shear, psi.	Fatigue Limit, psi.
Cast to size.....	84,000	.....
Ground from coupon.....	.....	39,000 ^a

^aDetermined with H. F. Moore type machine.

Electrical, Magnetic, and Thermal Properties—The electrical resistance of austenitic manganese steel is 71 microhms per cm.-cube, or 7 times that of pure iron; the average thermal conductivity between 0 and 100°C. is 0.027 cgs. units or about ¼ that of pure iron; and the mean coefficient of thermal expansion between 0 and 100°C. is 0.000018 per 1°C., or about 1½ times that of pure iron.¹

To all intents and purposes, manganese steel is nonmagnetic, that is, it has no attraction for the magnet. If a bar of the steel be placed across an ordinary field compass, the needle will be deflected only 1 or 2°. As yet very little practical use has been made of this property and for years the only application of the steel based on its nonmagnetic properties was the cover plates of electric lifting magnets, in which the power of resisting wear was also of value. Of late the attention of electrical engineers has been drawn to the subject and the steel is being applied to various transformer parts and other portions of electrical machinery where a strong, nonmagnetic metal is essential.

¹R. A. Hadfield, *Metallurgy and Its Influence on Modern Progress*, Chapman & Hall, Limited, London, 1925.

Determinations made of normal induction and magnetizing force gave results as follows:

Induction, Gausses	Magnetizing Force, Gilbert's per sq.cm.
10.....	9.5
20.....	18.4
30.....	27.3
50.....	44.8
70.....	62.5
100.....	89.3
150.....	136
200.....	183
250.....	231
300.....	279

The magnetic permeability, being the ratio of induction to magnetizing force, is nearly unity, the permeability of air, for the determinations in this table.

From Smithsonian Physical Tables, Sixth Edition, p. 321, the following figures are quoted for magnetic values in intense fields, the references given being the work of Ewing:

Magneto Motive Force	Magnetic Moment per cu.cm.	Magnetic Induction	Permeability
1930	55	2620	1.36
2380	84	3430	1.44
3350	84	4400	1.31
5920	111	7310	1.24
6620	187	8970	1.35
7890	191	10290	1.30
8390	263	11690	1.39
9810	396	14790	1.51

Hardening Power of Austenitic Manganese Steels—The Brinell hardness of the steel in the cast and in the heat treated condition is only moderately high, about 185 in the untreated condition and 180-200 after treatment. The correctness of this relatively low figure is confirmed by the fact that the steel can be dented with the peen end of a machinist's hammer, or nicked with a cold chisel, up to a certain point. The first blows of the hammer produce a considerable dent, but as the hammering proceeds the impression produced grows smaller and smaller, and finally a point is reached where the hammer hardly mars the surface, because the steel has grown much harder from the effect of the cold working. A Brinell test upon the cold worked surface shows a hardness of from 450-550, instead of the 180-200 of the heat treated steel. In fact, the rapidity with which this metal hardens under cold working of all kinds is extraordinary, and is probably responsible for its most valuable property, the ability to endure severe abrasion coupled with heavy pressure or blows.

Wear—Manganese steel owes its power of resisting heavy abrasive wear to the property of hardening under cold working to an extent approached by few other ferrous metals. The late Henry M. Howe first called attention to this phenomenon in a paper before the A.I.M.E.¹ In a jaw crusher, for instance, where the steel is subjected both to heavy pressure and severe abrasion, manganese steel will generally greatly outlast metals whose initial hardness is much greater. Tests have shown that the initial rate of wear of a manganese steel crusher jaw is somewhat greater than the rate after a few tons of stone have been crushed. This is due, of course, to the hardening of the steel by the kneading effect of the stone crushed. Jaws of other hard metals, such as nickel, chromium, and nickel-chromium steel, and chilled iron, show practically no difference in the rate of wear as the test progresses, and in consequence of their higher initial rate of wear and of the fact that this rate decreases little if any as the test progresses, jaws of these steels wear out after a life measured in terms of tons of stone crushed usually much less than that of manganese steel.

In wear of a different type, where cold working is largely absent, so that the steel is not surface hardened by the pressure, austenitic manganese steel does not

¹H. M. Howe and A. G. Levy, Are the Deformation Lines in Manganese Steel Twins or Slip Bands?, Trans., A.I.M.E., 1915, v. 51, p. 881.

outwear other metals to the same extent as in the typical case of crusher jaws. Under the action of the pure abrasion of a sand blast, for instance, chilled iron will outwear manganese steel, so that the latter does not make a satisfactory sandblast nozzle. In the many types of service where abrasion and cold working are encountered in varying proportions, the advantage of using manganese steel will depend largely upon whether there is enough pounding or pressure to produce a useful degree of hardening.

Applications of Austenitic Manganese Steels—Typical applications of cast high manganese steel are railway and trolley frogs, crossings and switches, rock crusher parts, steam shovel dippers and teeth, gold, platinum, tin, and gravel dredge buckets and lips, conveyor chain, sprockets, gears and pinions of many types, centrifugal pump parts for gravel dredges, ball and tube mill liners, rough paper making machinery, orange peel and clam shell dipper lips and points, tractor shoes and many others. Castings are furnished in all weights from a few ounces to 25,000 or even 30,000 lb. In the rolled condition the chief application is in rails used for special service, though a small amount is used for light forgings subjected to heavy wear, for woven screens, and some similar uses.

Machining—Largely because it hardens under and in front of the tool, heat treated austenitic manganese steel is machined only with great difficulty. For many years, in fact, all efforts to machine it commercially were failures, and finishing operations were universally carried out in grinding machines. Of late years some manufacturers of manganese steel have found that by using exceedingly heavy, rigid machine tools and the most modern tool steels, some machining operations can be carried out more economically than grinding. In general, steel tools are better suited to this work than the cemented carbides and similar metals, because under the heavy pressures required to cut manganese steel successfully, the more brittle metals are likely to break and spall. The great majority of the finishing work on manganese steel castings is still performed with grinding wheels.

Welding—Until comparatively recent years, gas or electric welds in manganese steel have been unsatisfactory, because the heat of the arc or torch damaged the manganese steel close to the weld, making it brittle. Periodic quenching of the weld does not prevent this brittleness, because it is due to two effects upon the metal, one of which is curable only by reheat treating the whole casting, and the other is curable only in part by any thermal or mechanical treatment.

A welding rod has recently been developed containing from 3-5% nickel and 13-15% manganese, with carbon generally from 0.60-0.80%. With this, welds in manganese steel are made which develop from 50-60% of the strength of the unwelded metal. The combined effect of the nickel and the low carbon content is to greatly strengthen and toughen the "contact zone" of manganese steel close to the weld line, in which failure occurs when welding rods of composition similar to that of the castings are used. The adoption of these low carbon-nickel-manganese steel rods has resulted in making the fusion welding of manganese steel commercially successful, and many difficult welds of worn and cracked parts are now giving satisfactory results in severe service.

Some authorities on welding prefer to use welding rods or electrodes of the 18 Cr -8 Ni type for welding cracked or broken manganese steel parts, covering the welds over with manganese steel to obtain good wear resistance in the welded area. The author's experience has been that stronger and more satisfactory welds are obtained with the nickel-manganese steel rods described above.¹

Special Compositions—Austenitic manganese steels containing varying amounts of other alloys have been made in recent years. One of these steels whose application is the welding rod described above, has been found to roll and forge more easily than manganese steel of standard analysis, and to be less easily damaged by exposure to temperatures just below dark red heat. In the form of bars, sheet, and plate it is to some extent displacing rolled products of the older Hadfield range of composition. Car bearing parts, woven screen, and similar applications have proven successful uses of the rolled material containing 13-15% manganese and 3-5% nickel. In the cast condition, a similar alloy containing also about 4%

¹See J. H. Hall, A.S.T.M. Symposium on Welding, 1931, page 62.

" Welding Engineer, 17(1) 39-41, 1932.

" Electric Traction, 27, 400-402, 1931.

" Welding Handbook, A.W.S., p. 544, 1938.

Howard George, Electric Traction, March 1931.

chromium is finding applications in resisting wear combined with temperatures approaching red heat.¹

One of the difficulties experienced with manganese steel is its peening and stretching under heavy pressure. In extreme cases, manganese steel parts will "grow" enough to cut off the heavy bolts with which they are held in place, or to buckle so badly as to interfere with the operation of the machine of which they form a part. This tendency to "grow" has always been taken care of by making such parts enough smaller than the space they are eventually to fill, to permit growth to occur without harmful results.

Many efforts have been made to counteract this tendency, which is due of course to the comparatively low compressive elastic limit of the material, by the addition of other alloys to the steel. Chromium up to some 6%, molybdenum up to about 1%, or combinations of the two, are the alloys usually preferred. Additions of these "hardeners" of sufficient amount to decrease the tendency to peen, decrease the toughness of the steel to a considerable extent. To overcome this loss of toughness, additions of nickel as above described, or of copper up to some 2%, have been sometimes made. Not enough service tests have been carried out on these special compositions to justify a definite statement as to their value, but the indications are that in some cases the extra cost of the alloy is justified by the improvement in the results secured in service.

Pre-Peening—As manganese steel develops its full resistance to wear only after the surface layers have been deformed by pressure and consequently hardened, in some applications of the metal it is advantageous to perform this deformation artificially. This is especially desirable when it is important that the exact shape of the piece be maintained as nearly as possible, as for instance in street and steam railway special trackwork. In these cases, the part is finished to a little above the desired final dimensions, at places where distortion takes place, and these parts are brought to the final dimension by cold working by means of press, hammer or air hammer. In this manner, the part can be shipped in condition to give the best resistance to wear from the start, without being distorted out of shape while developing this desirable condition.

It has not been found economical to utilize this method to improve the wear resistance of manganese steel in classes of service to which it is not otherwise suited, such as described above, because the depth of metal hardened by artificial cold work bears too small a relation to the total thickness to be worn away in service.

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- ⁴J. H. Hall, *Welding Manganese Steel*, Elec. Traction, 1931, v. 27, p. 400.
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¹See J. H. Hall, *Metal Progress*, 20, 69-72, Nov. 1931.
"A New Nickel-Manganese Steel."

Molybdenum Steels

By A. J. Herzig* and W. P. Sykes†

Pure molybdenum is a soft, ductile metal resembling platinum in color. Its physical constants are given in this Handbook under "Physical Constants of the Elements."

The metal is produced by heating one of its several oxides, or ammonium molybdate, in an electric furnace and reducing in hydrogen to pure molybdenum powder. The compressed powder is sintered by passing a strong electric current through it. The resulting ingot is swaged, rolled, and drawn into sheets, rods and wire. The pure metal is used for the spider of incandescent lamps, for parts of radio tubes, X-ray equipment, electrical heating units, and in the manufacture of non-ferrous alloys.

Historical—Molybdenite was first distinguished from graphite and galena in 1778 by C. W. Scheele. In 1782, P. J. Hjelm separated the metal from molybdenite and called it *molybdenum*. Metallic molybdenum was produced by Berzelius at the beginning of the 19th century. Although the presence of molybdenum in alloys of iron was established as early as 1831 by analysis of several iron-rich meteorites, the first intentional production of iron-molybdenum alloys was accomplished by Moissan about 1880 in his work with the electric arc furnace. From this date references to the application of molybdenum became increasingly numerous and at the opening of the 20th century it was in commercial use in high speed steel although this application was short-lived. Studies of molybdenum steels were made by Guillet (1904) and Swinden (1911). Out of the demands of the World War for new materials much information on molybdenum steels was obtained. Molybdenum steel was definitely adopted as a standard specification by one of the large automobile plants in 1920. Since then the commercial use has grown rapidly.

Supply and Production—Although a small amount of molybdenum is recovered from Wulfenite (PbMoO_4), the most important ore of molybdenum is molybdenite (MoS_2). This is a soft, flaky, lustrous mineral, similar in appearance to graphite. Mineralogically, it is widely distributed throughout the world, but commercial occurrences are relatively rare. The largest known deposits are in the United States.

Molybdenite is extracted from its usual low grade ores by fine grinding and flotation concentration. The concentrate, containing about 50% molybdenum and 35% sulphur, is calcined to remove the sulphur and the resultant crude molybdic oxide (MoO_3) is the base material from which the various compounds and alloys of commerce are produced.

Introduction of Molybdenum into the Steel Bath—Molybdic oxide briquettes, a salt of molybdenum (calcium molybdate or calcium molybdenum silicate) or ferromolybdenum may be employed for making additions of molybdenum to the steel bath. The salt or oxide is lower in cost and satisfactory for introducing all fractional percentages of molybdenum. Molybdenum has a low affinity for oxygen and the elements of the steel bath. Molten iron will reduce molybdenum from the slag in which the molybdate or oxide has been dissolved. All other compounds of the salt are slag forming constituents, and only pure nascent molybdenum enters the steel. When more than 1% molybdenum is required, ferromolybdenum is preferably employed.

Effect of Molybdenum in Steel—In solid solution molybdenum is known to expand the space lattice of iron. In steel molybdenum will be found both in the solid solution phase and in the carbide phase. It tends to inhibit grain growth and definitely imparts sluggishness to any structural change which is induced by thermal treatment. This effect is clearly demonstrated by the higher requirements in quenching and tempering temperatures for the heat treatment of steels containing molybdenum. There is strong evidence that molybdenum markedly raises the lowest temperature of recrystallization of iron.

Molybdenum steels require relatively longer soaking periods for annealing and spheroidize more slowly than carbon steels. The depth hardening characteristics are decidedly more pronounced than would be predicted on the basis of the change in equilibrium transformation temperatures. The critical transformation of steel containing molybdenum is sluggish so that with the cooling rates normally

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encountered in practice, deep hardening is readily attained. Molybdenum steels are generally characterized by the following properties: Depth hardening; toughness; structural stability; elevated temperature strength; minimum susceptibility to temper brittleness.

Molybdenum in small amounts does not interfere with forging, rolling, machining, carburizing, or welding operations. In many instances steel containing molybdenum is found to harden acceptably from an unusually wide range of heating temperatures. Chromium-molybdenum steel is well known for its self scale freeing characteristics. It is common knowledge that chromium-molybdenum steels of the 4100 series in the fully heat treated condition can be machined at higher hardnesses than other alloy steels of comparable physical properties. In regard to welding, it is claimed that molybdenum is the one element besides phosphorus which can be added to iron without seriously affecting the ability of iron to be welded.

Chromium-Molybdenum Steels—Steels properly alloyed with chromium and molybdenum are characterized by their resistance to impact, fatigue, abrasion and high temperature stress. These steels when suitably heat treated are deep hardening, offer good machinability and are readily welded by either gas or electric methods. The composition for the S.A.E. steels is given in the S.A.E. specification in the Handbook, and the heat treatments for steels here considered are in Table I.

Table I
Suggested Heat Treatments for Molybdenum Steels

S.A.E. No	Normalize, °F.	Anneal, °F.	Quench, °F.	Temper Footnote ^a
4130	1600-1700	1525-1575	1550-1600 Water 1575-1625 Oil	As required
4140	1600-1700	1500-1550	1525-1575 Oil	"
4150	1600-1700	1475-1525	1500-1550 Oil	"
4320	Carburize 1650-1700 ^b	1525-1575	1400-1450 Oil for Case 1450-1500 Oil for Core	"
4340	1575-1675	1525-1575	1500-1550 Oil	"
4615	Carburize 1650-1700 ^b	1550-1600	1425-1475 Oil for Case 1475-1525 Oil for Core	"
4620	Carburize 1650-1700 ^b	1525-1575	1425-1475 Oil for Case 1475-1525 Oil for Core	"
4640	1600-1750	1525-1575	1500-1550 Oil	"
4815	Carburize 1650-1700 ^b	1525-1575	1350-1400 Oil for Case 1450-1500 Oil for Core	"
4820	Carburize 1650-1700 ^b	1525-1575	1350-1400 Oil for Case 1450-1500 Oil for Core	"

^aA long soak is recommended. ^bBox quench.

S.A.E. Steel 4130—This composition is recommended for heat treated automobile parts such as driveshafts, rear axle shafts, steering knuckles and arms, connecting rods. Other established applications include aircraft tubing, intake valve stems, drill collars, sucker rods, bolts and studs.

S.A.E. X4130—This analysis has higher chromium and lower manganese than S.A.E. 4130. The most extensive application is airplane construction; it is also used interchangeably with S.A.E. 4130. The heat treatment is the same as for S.A.E. 4130.

S.A.E. 4140—This steel is intended for practically the same purpose as 4130 except that it is oil quenched and the physical properties are slightly higher.

S.A.E. 4150—This steel is recommended for heat treated parts which are subjected to wear, such as gears and roller bearings; also for highly stressed automobile and machine parts.

Nickel-Chromium-Molybdenum Steels—In heavier section, these steels offer the best combination of ductility and strength and the highest fatigue-tensile ratio of any molybdenum S.A.E. steels. Being air hardening, the steels must be prepared for machining by a suitable annealing treatment. Because of their deep hardening characteristics and resistance to softening at elevated temperatures, these steels, with suitable carbon content, are recommended for hot work dies.

S.A.E. Steel 4320—This steel is similar in analysis to S.A.E. 4620 except for the chromium content. Its field of usefulness lies in those carburized parts which require a somewhat harder and stronger core than is normally developed with S.A.E. 4620.

S.A.E. Steels 4340 and X4340—These steels are recommended for oil hardening gears, axle shafts, crankshafts, and heavy duty shafting of large sections. When quenching large section, the best practice is to remove the work from the quenching medium before it becomes cold.

Chromium-nickel-molybdenum steels outside the S.A.E. classifications are often used for parts such as gears, shafts and axles; in the higher carbon range, these steels are recommended for special gears, drop forge die blocks, airplane propeller shafts and heavy forgings.

Nickel-Molybdenum Steels—This alloy combination is characterized by excellent toughness at relatively high hardness. The hardening range is wide and quenching from the carburizing temperature without objectionable distortion or impairment of physical properties may be successfully employed.

S.A.E. 4615 and S.A.E. 4620—These steels are used in carburized gears, cams, and shafts where high fatigue resistance and good toughness are required. They are good carburizing steels from the standpoint of minimum distortion. For best results, after quenching, the carburized article should be held for a prolonged period of time at a low temperature (300-400°F.).

S.A.E. Steel 4640—With its higher carbon content this steel is used for gears, shafts, and parts where high fatigue resistance is required. Like the lower carbon steel, it affords minimum distortion problems.

S.A.E. 4815 and S.A.E. 4820—These steels are used for carburized gears and parts where high core hardness is required.

Carbon-Molybdenum Steels—Cases where the necessity for welding or some other condition which precludes the presence of chromium, form the principal field for the straight molybdenum steels. Among the advantages of this composition are resistance to grain growth and minimum susceptibility to temper brittleness. These steels are adapted to welding and possess excellent creep resistant properties. Representative applications include automobile parts, structural plates, welded pipes, crankshafts, boiler, and still tubes.

Manganese-Molybdenum Steels—Steels containing 1.5-2.5% manganese are generally susceptible to extreme temper brittleness, but the addition of molybdenum strengthens the steels statically and dynamically, minimizes temper brittleness, stabilizes the properties at elevated temperatures, refines the structure, and widens the critical range. Railway rails and locomotive tires, dredge buckets and rock crusher parts and high tensile studs are typical applications.

Silicon-Molybdenum Steels—Molybdenum additions to silicon steel serve to increase toughness, reduce the tendency toward temper brittleness and resist grain growth at elevated temperatures. Chisels, shear knives, hammers and similar shock resisting tools are produced from silicon-molybdenum steels.

Molybdenum High Speed Steel—While the use of relatively small percentages of molybdenum in tool and die steels has been common for a number of years, it is only recently that tool steel in which molybdenum is the chief alloying element has gained much prominence. A steel containing 8.00-9.00% molybdenum with or without 1.50-2.00% tungsten is now being produced commercially. The advantages are: Lower cost, lower density, and lower required hardening temperatures. Susceptibility to surface decarburization when treated in oxidizing atmospheres has retarded its universal acceptance. This surface decarburization is satisfactorily overcome by the use of salt baths, borax coatings, or controlled furnace atmospheres.

Molybdenum Die Steels—Die steels properly alloyed with molybdenum are characterized by deep hardening, resistance to abrasion, heat checking and washing. Hot work tools and dies, forging rolls, punches, upsetting and extruding dies are among the recommended applications.

Corrosion Resistant Alloys—Copper-molybdenum iron is used to resist atmospheric and mild acid attack. In many instances, molybdenum additions to standard 18-8 steels increase the strength of the composition at elevated temperatures and improve resistance to corrosion.

Molybdenum Steels for Elevated Temperature—Molybdenum steels retain their hardness and strength at elevated temperatures. Carbon-molybdenum steels are used in oil refineries for convection tubes and cracking furnace tubes and as steam piping for boiler plants. Repeated tests show resistance of carbon-molybdenum steel to creep to be about twice that of carbon steel at 900°F.

Molybdenum in Steel Castings—The properties imparted to forged and rolled steel by molybdenum are similarly exhibited in steel castings. The following types

are common: Carbon-molybdenum, chromium-molybdenum, manganese-molybdenum, nickel-molybdenum, chromium-nickel-molybdenum.

Carbon-molybdenum cast steel is used for castings required to show good strength at elevated temperatures. Chromium-molybdenum cast steel provides improved depth hardening characteristics to the castings, high temperature strength and abrasion resistance. Special types of chromium-molybdenum cast steel are also used for resistance to oxidation and corrosion. Manganese-molybdenum compositions are used where general improvement of tensile and impact characteristics are required. Chromium-nickel-molybdenum cast steel finds its application in parts where maximum depth hardening characteristics are essential and where severe abrasive service must be withstood.

Mill Rolls—One of the important uses of molybdenum in steel castings is in mill rolls where it is usually employed in conjunction with chromium, nickel, or both. These rolls are characterized by great strength, toughness, density and wearing qualities. The carbon content varies widely from 0.40-2.00% according to the service to be encountered or according to which of the above physical characteristics is of first importance. Heat treatments vary likewise from slow furnace cooling to air quenching followed by tempering. With the heavy masses involved, bath quenching is impractical. Molybdenum is used to advantage in cast steel and cast iron rolls, both chilled and sand cast.

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Nickel As An Alloying Element in Steel

Thomas H. Wickenden*

Historical—The occurrence of nickel in meteorites and the working of this material into swords and tools undoubtedly accounts for the first use of nickel steel. Nickel, however, as an element was not recognized until isolated by Cronstedt in 1751. The first published report of its being alloyed with iron was by Stoddard and Faraday¹ in 1820. The next important development was the production started in 1885 by Marabeau of a wide series of iron-nickel alloys and nickel steels. These were studied and tested by James Riley of Scotland and the results were published in his now famous paper of 1889 on the "Alloys of Nickel and Steel." He was the first to demonstrate the general properties of nickel steels and pointed out their commercial value. During this period nickel had gradually become more available and cheaper because about this time nickel was produced in commercial quantities from both the New Caledonian and Canadian ores.

Riley's paper marked the beginning of active engineering and metallurgical interest in these steels. In 1891 the U. S. Navy conducted a competitive test between plain carbon and nickel steel armorplate. The nickel steel proved decisively superior and stimulated a world wide interest in this material for ordnance. In 1899

Hadfield² published an exhaustive paper on the "Alloys of Iron and Nickel." Since then it has been the subject of active interest and investigation by many scientists, and today finds an exceedingly wide field of industrial applications.

Alloying Nickel in Steel—Nickel is a white, malleable, magnetic metal, harder and stronger than iron, and has a melting point of approximately 2645° F. Nickel is supplied in the form of electrolytic cathode of

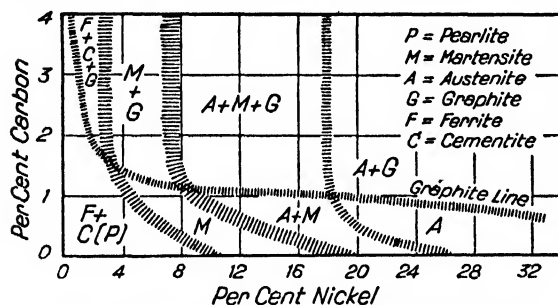


Fig. 1—Constitution diagram of nickel steel and iron.

high purity (99.90% Ni + Co) sheared to convenient sizes. It is also available in the form of shot and ingot of remelted cathode. As nickel is not oxidized in the bath, in fact nickel is chemically negative to the iron, it may be added at any time practically without loss. Part of the nickel is generally secured by charging nickel steel scrap; the balance may be added with the charge or at sufficient time before tapping to ensure proper diffusion. As nickel has no deoxidizing properties, it does not prevent blowholes, hence the steel to which it is added should be well made. Nickel does check segregation and tends to produce a fine grain primary crystal but is primarily added to steel for its beneficial effect on the mechanical properties.

The Effects of Nickel in Steel—Iron and nickel are soluble in all proportions in the molten state and remain as a solid solution on solidification. At normal temperatures nickel is in solid solution in the iron phase, either ferrite or austenite, depending on the composition. The equilibrium diagram of iron and nickel is given in another section of this Handbook. An examination of this shows some of the fundamental effects of adding nickel to iron. The addition of nickel reduces the temperature of the A_c3 transformation and introduces a considerable spread between the temperature of beginning and the end point. The A_r point is reduced to a still greater extent, in fact with 33-34% of nickel it is not reached at liquid air temperatures.

The constitution diagram for nickel, iron and carbon, after commercial slow cooling, is given in Fig. 1. The graphitizing effect of nickel is shown by the graphite line. The change in structure of these nickel-iron-carbon mixtures as the nickel or carbon is increased is not sharply defined but changes gradually over a considerable variation in composition. This is true when the pearlitic area—generally

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¹The Quarterly Journal of Science, Literature and the Arts, 1820, v. IX, p. 324.

²R. A. Hadfield, Alloys of Iron and Nickel, Proc., Inst. Civil Engrs. (London), 1899, v. 138, p. 1.

as a fine grained sorbite—enters the martensitic area by showing some martensitic needles.

Because traces of austenite soon make their appearance, the range where martensite alone is found is rather narrow. The martensitic structure in the lower carbon range is often difficult to identify as it will show martensitic like needles but does not possess the hard properties characterizing this constituent. The mixed structure of martensite and austenite extends over a broad area, the last traces of martensite persisting up to a fairly high nickel content under conditions of slow cooling.

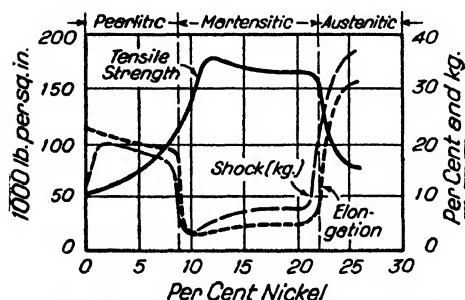


Fig. 2—Comparative physical properties of nickel steels with 0.25% carbon. Not heat treated (Bullens).

The general effect of increasing quantities of nickel on the mechanical properties of a cast nickel steel with 0.25% carbon is illustrated in Fig. 2. The strength is gradually increased, reaching a maximum of 180,000 psi., with 12% of nickel. Data on carbonless nickel-iron alloys, annealed, by Burgess and Ashton show the same maximum strength, but at 18% of nickel. The strengthening effect of nickel on ferrite should be noted as it offers a means of strengthening low carbon steels without heat treatment. Carbon has the effect of shifting the diagram to the left and accentuating the martensitic stage. It should be noted from

the diagram that the abrupt changes in mechanical properties correspond to the changes in the micro-constituents of the steel.

Classification of Nickel Steel—Characteristics of the 3 groups of steels pearlitic, martensitic, and austenitic are discussed in detail.

The Pearlitic Steels—The pearlitic group, steel containing from 0.5-6.0% nickel, is most widely used commercially. The principal effects of nickel on this group of steels are as follows:

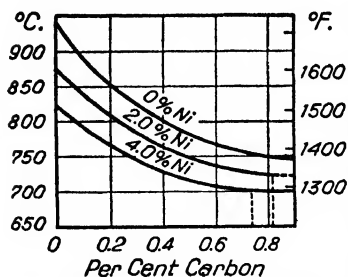


Fig. 3—Effect of Nickel on the AC Critical Range.

1. Nickel depresses the critical point and lowers the eutectoid ratio. The effect of nickel in lowering the Ac critical range is well illustrated by Scott¹ in Fig. 3. He further states that the Ac₁ is lowered 18.9°F., the Ar₁ 38.7°F., and the eutectoid ratio is decreased approximately 0.042% carbon for each per cent of nickel added. Thus, with a normal eutectoid ratio of 0.90% carbon in plain carbon steel this is reduced to approximately 0.75% for 3.5% nickel and 0.70% for 5.0% nickel steel. The lower critical range allows the use of lower quenching temperature when heat treating nickel steels, and consequently results in less scaling, warping, and cracking of the part. This also permits a saving of fuel and less wear on the heat treating equipment.

2. Nickel increases the strength, yield point, and hardness without a corresponding loss of ductility in both the annealed and heat treated steels. The following table gives data on an annealed 0.30% carbon steel with different nickel contents.

Carbon	Nickel	Tensile Strength, psi.	Yield Point, psi.	Elongation in 2 in., %	Reduction of Area, %	Brinell Hardness No.
0.30	0	70,000	40,000	26.0	50.0	145
0.30	3.50	90,000	60,000	27.0	55.0	175
0.30	5.00	95,000	65,000	28.0	56.0	185

These characteristics of nickel are utilized in rolled structural shapes, boiler plates, and large forgings or castings which, due to size or shape, are impractical to heat

¹Bur. Standards Bull. No. 376, p. 212. Critical Ranges of some Commercial Nickel Steels.

treat beyond normalizing and annealing. Nickel, often in combination with copper, is used in many of the recently developed high tensile, medium corrosion resistant steels which are generally used in the as-rolled condition. In some of the nickel-copper steels the tensile strength can be further increased by precipitation hardening treatment.

Abbott,⁴ after a great many tests, observed the average effect of nickel up to 8%, for fully annealed steel, to be as follows:

1.0% of nickel increased the elastic limit.....	4,000 psi.
1.0% of nickel increased the tensile strength.....	4,200 psi.
1.0% of nickel increased the reduction of area.....	0.5%
1.0% of nickel decreased the elongation.....	1.0%

If steels of the same strength and similar treatments are compared, the advantages of nickel in increasing the yield point, impact, fatigue limit, and fatigue ratio are very evident. The following results taken at mid point in 6 in. forgings, normalized and tempered illustrate these points:

C	Mn	Ni	Yield Point, psi.	Tensile Strength, psi.	Izod Impact, ft.-lb.	Fatigue Limit, psi.	Fatigue Ratio %	Brinell Hardness
0.46	0.64	....	51,300	86,200	16	40,000	47	167
0.24	0.94	2.70	57,800	87,800	86	54,000	61	183

In heat treated steels the benefit of nickel is still more evident as shown by the following results from a 0.40% carbon steel and a 3½% nickel steel.

Steel	Heat Treatment	Tensile Strength, psi.	Yield Point, psi.	Elong. in 2 in., %	Red. Area, %	Izod Impact, ft.-lb.
0 Nickel	1500°F.—Water; 1300°F.	90,000	53,000	25	62	59
3.5% Nickel	1425°F.—Oil; 1250°F.	109,000	85,000	25	62	76
0 Nickel	1500°F.—Water; 980°F.	125,000	82,000	18	51	36
3.5% Nickel	1425°F.—Oil; 1090°F.	126,000	104,000	23	60	59
0 Nickel	1500°F.—Water; 600°F.	150,000	112,000	9	34	13
3.5% Nickel	1425°F.—Oil; 910°F.	150,000	137,000	18	56	36

3. Nickel slows down the critical rate of hardening. This property affects its use in several ways. Oil can be used as a quenching medium which reduces the danger of warping or cracking on intricate shapes. The depth hardening properties of nickel steels can be greatly augmented by the addition of molybdenum or chromium; with these additions parts of large size can be hardened to considerable depth. Slow cooling tends to produce a fine grain pearlite tending toward sorbite.

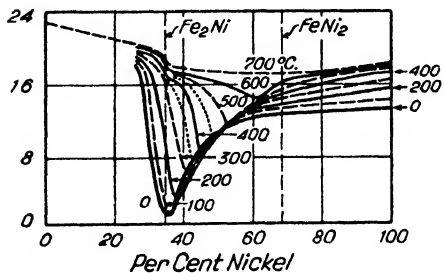


Fig. 4.—Variation in the true coefficient of linear expansion of nickel steels at various temperatures (Chevenard).

uniformity of carbon penetration. They are amenable to a single quenching treatment; they develop greater core strength; and the case is tougher as shown by a smaller tendency of the nickel steels to show grinding cracks. The case will develop file hardness on oil quenching.

⁴R. R. Abbott, In his: *Rôle of Nickel*. Proc., A.S.T.M., 1917, v. 17, pt. 2, p. 11.

5. Nickel increases the resistance to fatigue endurance ratio. McAdam⁵ states the addition of nickel to annealed carbon steel apparently strengthens the ferrite with the result that the endurance ratio is raised. The full effect of nickel on the endurance ratio, however, is obtained only by quenching and tempering.

6. Nickel increases the resistance of steel to corrosion. This is easily demonstrated by the resistance to etching shown by 5.0% nickel steels. The use of nickel in the high tensile, medium corrosion resistant steels has been mentioned above.

7. Nickel improves the impact properties of steel as shown in the table above. This shows that at equal tensile strengths the nickel steel is tougher and has greater resistance to shock, especially as the tensile strength is increased. Nickel toughens steel at low temperatures and its favorable influence is exerted alike on cast and wrought steels. Room temperature tensile and low temperature impact properties of normalized and tempered, rolled 2% nickel steel and a double normalized and tempered, low carbon, cast 3½% nickel steel are shown in the following:

% C	% Mn	% Ni	Yield Point, psi.	Tensile, psi.	Elong., %	Red. Area, %	Charpy Impact, ft.-lb. Keyhole Notch			
							70°F.	-75°F.	-150°F.	-200°F.
0.08	0.48	1.99	47,000	61,500	40.0	70.0	63	62	39	26
0.13	0.65	3.50	53,500	80,000	32.0	60.0	38	26	20	18

Both steels were treated with 0.08% aluminum. The tempering temperature was 1200°F.

8. Nickel is extensively used in welding grade of steels. As nickel strengthens ferrite without the presence of carbon, it does not increase the weld hardness as drastically as some of the carbide forming elements. It is widely used in conjunction with other alloys in the high elastic steels of welding quality.

The nickel-chromium steels are produced with a wide variety of compositions. The analyses, properties, and further data on the applications and heat treatment of these alloys are given in other articles of this Handbook and the S.A.E. Handbook.

Nickel-molybdenum makes an excellent carburizing steel and nickel-chromium-molybdenum an excellent steel for heavy sections requiring high strength and good impact properties.

Nickel-silicon and nickel-silicon-molybdenum steels were developed during the late war period for light armor plate. They show unusual combinations of properties at high strengths.

Martensitic Steels—This group with 10-22% of nickel is not much used. The steels are hard, almost impossible to machine; certain combinations are brittle, and give very little response to heat treatment.

Many corrosion resistant steels will be found with nickel within this range but it is usually in combination with other elements which tend to make the steel austenitic.

Austenitic Steels—The austenitic range of nickel steels presents a most fascinating study as their properties are so varied that they constantly unfold new and interesting engineering and scientific applications.

The straight iron-nickel group has a variety of uses as follows:

25-30% Nickel—Alloys with this nickel range are used for corrosion resistance and for low temperature electrical resistance wire.

20-30% Nickel—Steels with this nickel range are nonmagnetic after cooling at normal rates from forging or rolling temperatures to atmospheric temperature. Their magnetic condition can be restored by cooling to liquid air temperature.

30-40% Nickel—This nickel range presents an interesting anomaly in coefficient of expansion. As the nickel content is increased above 30%, the coefficient of linear expansion is rapidly lowered until it reaches a minimum of nearly zero coefficient between 35 and 36% of nickel. This phenomenon was discovered by Guillaume, and to carefully prepared and heat treated alloys of this composition he gave the name of "Invar." In its finer state it is used for the production of fine instruments, standard bars, measuring tapes, clock pendulums, balance wheels of watches, and as one of the bimetals used for thermo controls. In a more commercial grade with wider range of nickel this alloy is finding use as struts in aluminum pistons to control the overall expansion to that of cast iron. At elevated temperatures the point of minimum expansion is lower with higher nickel ratios as is shown in Fig. 4.

Elinvar—Elinvar is an alloy having a nonvariant elastic modulus with tem-

⁵D. J. McAdam, Jr., On Endurance Properties of Steel, A.S.T.M. Proc., 1923, v. 23, pt. 2, p. 99.

perature change. It was developed by Guillaume and the original composition contained approximately 36% of nickel and 12% chromium. This composition has been modified so that most of the Elinvars used for hair springs have a chromium range of 4-5%.

Platinite—Platinite is a nickel steel with about 46% nickel which has the same coefficient as platinum.

50% Nickel—An alloy of 50% nickel and iron is used for its magnetic properties, having a high permeability at low field strengths. It is finding application in the radio field.

78.5% Nickel—This is another magnetic nickel-iron alloy with high permeability at low field strengths; also the magnetic hysteresis loss is very low. It is finding use in telephone equipment and as loading tape in submarine cables. It is known as Permalloy.

Nickel in Cast Steel—Nickel is extensively used as an alloy addition to cast steels. The amount used varies from 0.5-5% and is often used in conjunction with other alloying elements. Analysis, heat treatment, and mechanical properties of cast nickel steels that have been widely used are given in Table I.

Corrosion and Heat Resisting Alloys—Nickel is one of the important constituents in this group of alloys and is used in a wide range of compositions in combination with many other elements. For further information on compositions, see the sections of this Handbook dealing with stainless steels and trade names of corrosion and heat resisting alloys.

(Table I on next page)

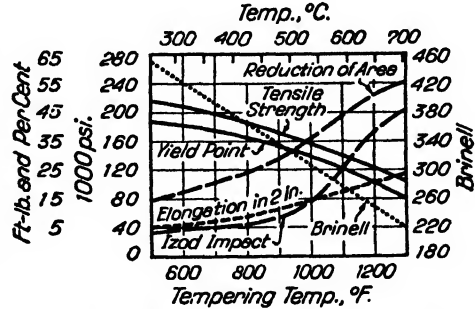


Fig. 5—Properties of cast nickel-chromium-molybdenum steel. C, 0.25-0.35; Mn, 0.60-0.80; Ni, 1.75-2.25; Cr, 0.60-0.90; Mo, 0.15-0.25; water quenched from 1550°F. (Bonney Floyd Co.)

Table I
Cast Nickel Steels
(1 in. Sections)

% C	% Mn	% Ni	% Cr	% Mo	% V	Heat Treatment, °F.†	Yield Point, psi.	Tensile Strength, psi.	Elong., % in. 2 in.	Red. Area, %	Brinell Hardness
<i>Constructional Castings</i>											
0.20 max.	0.60/0.90	2.00 min.	.....	.....	.....	D. N. and T. 1200	50,000	80,000	28.0	55.0	163
0.25/0.35	0.80/1.10	1.75/2.25	.....	.....	.....	N. and T. 1050-1225	62,000	95,000	25.0	50.0	197
0.30/0.40	0.60/0.90	3.00/3.50	.....	.....	.....	Full anneal	60,000	90,000	23.0	40.0	185
0.25 max.	0.50/0.80	1.40/1.75	.....	.....	0.06/0.12	D. N. and T. 1100-1225	56,000	80,000	28.0	50.0	163
0.28/0.35	0.80/1.10	1.40/1.75	.....	.....	0.08/0.15	N. and T. 1100-1225	65,000	95,000	26.0	55.0	197
0.25/0.40	0.90/1.25	0.80/1.25	.....	.....	.....	N. and T. 900-1250	58,000	88,000	23.0	45.0	180
0.28/0.33	1.35/1.65	1.20/1.50	.....	.....	.....	N. and T. 1000-1225	65,000	95,000	26.0	50.0	197
0.25/0.35	0.60/1.00	1.25/1.75	.....	0.25/0.35	.....	N. and T. 1000-1225	65,000	90,000	28.0	50.0	184
0.30/0.40	0.60/0.90	1.50/1.75	0.40/0.65	.....	.....	N. and T. 900-1250	70,000	105,000	20.0	45.0	223
0.30/0.40	0.60/0.90	1.50/1.75	0.40/0.65	0.20/0.35	.....	N. and T. 950-1250	80,000	110,000	19.0	40.0	237
<i>For Service at Temperatures 750-1100°F.</i>											
0.45 max.	1.00 max.	1.75/2.25	0.75/1.25	.....	.....	N. and T. 1150-1225	68,000	100,000	22.0	40.0	207
0.48 max.	1.06 max.	1.75/2.25	0.75/1.25	0.30/0.60	.....	N. and T. 1150-1225	70,000	105,000	22.0	42.0	223
0.43 max.	1.00 max.	1.75/2.25	0.75/1.25	0.40/0.80 W	.....	N. and T. 1150-1225	68,000	105,000	21.0	38.0	223
0.28 max.	0.70 max.	0.75/1.05	0.40/0.70	0.30/0.55	.....	N. and T. 1100-1225	60,000	86,000	24.0	45.0	175
<i>For Resistance to Wear and Abrasion</i>											
0.30/0.40	0.50/0.80	3.00/3.50	.....	.....	.....	W. Q. and T. 1050-1225	125,000	135,000	17.0	40.0	290
0.30/0.45	0.90/1.25	0.80/1.25	.....	.....	.....	W. Q. and T. 900-1250	96,000	120,000	17.0	40.0	262
0.30/0.40	0.60/0.90	1.50/1.75	0.40/0.65	0.20/0.35	.....	O. or W. Q. and T. 1000-1225	135,000	150,000	18.0	35.0	325
0.40/0.50	0.60/0.90	1.75/2.25	0.60/0.90	0.25/0.35	.....	N. and T. 1050-1225	75,000	110,000	18.0	35.0	235
0.55/0.70	0.50/0.80	1.50/2.00	0.90/1.25	0.25/0.35	.....	N. and T. 900	.....	.....	.....	.....	.....
0.60/0.80	10.0/15.0	3.00/5.00	.....	.....	.....	W. Q. 1800	.....	100,000	50.0	.....	.....

*Welding grade.

†N = normalized; D. N. = double normalized; T = tempered; W. Q. = water quenched; O = oil.

Properties of Iron-Nickel Alloys

By J. W. Sands*

Iron and nickel are soluble in all proportions in the molten state and form solid solutions on solidification. The alloys at room temperature may be either

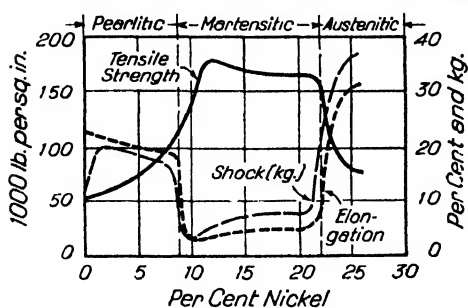


Fig. 1—Comparative physical properties of nickel steels with 0.25% carbon. Not heat treated (Bullens).

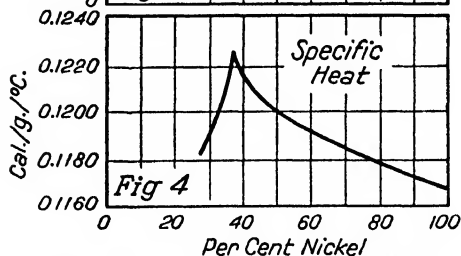
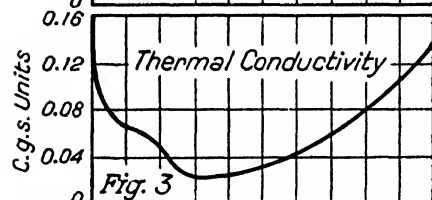
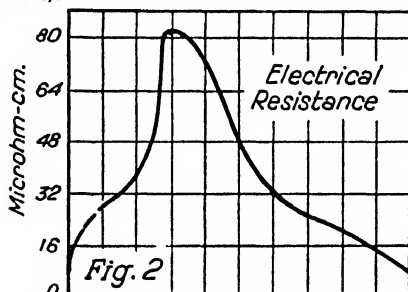


Fig. 2—Variation of electrical resistance with nickel content in iron-nickel alloys. Multiply by 6 to convert to ohms per mil. ft.

Fig. 3—Variation of thermal conductivity (Cgs. units) with nickel content in iron-nickel alloys. Multiply by 2900 to convert to English units. (Ingersoll.)

Fig. 4—Variation of specific heat in cal. per g. per °C. with nickel content in iron-nickel alloys. (Ingersoll.)

36% nickel, but increases on either side of this composition, making it possible in the

ferritic or austenitic in nature depending upon the nickel content and in some cases on the thermal history of the sample. Additions of carbon also affect the phase relationships. Nickel progressively lowers the transformation temperature of iron, imparts a considerable hysteresis in the temperature of its occurrence on heating and cooling, and introduces a considerable spread between the temperature of beginning and end points. The lowering of the Ar range is so pronounced that at a nickel content of about 34% the transformation cannot be reached even at the temperature of liquid hydrogen (20°C. above absolute zero). Hence all the alloys containing nickel in excess of this amount are austenitic (face-centered cubic) under all conditions. See page 386 on the constitution of iron-nickel alloys.

Alloys of lower nickel content may be either ferritic or austenitic or a mixture of both, depending on the thermal history of the sample. Under ordinary conditions of commercial slow cooling, the alloys with between 10-25% nickel possess a martensite-like structure which is relatively hard and non-ductile. Little commercial use is made of alloys in this range.

Under the same conditions of slow cooling, carbon-free alloys containing less than 10% nickel are simple, single phase solid solutions of nickel in alpha iron. In the presence of carbon these alloys become amenable to the ordinary methods of heat treating steel and, in general, assume the usual microstructures associated with pearlitic steels, although some austenite is likely to be retained in the case of the higher nickel contents. Nickel contents up to 6% are used commercially in automotive and engineering steels to provide advantages discussed elsewhere in this book. For similar reasons nickel in these proportions is also widely used in engineering cast irons.

The iron-nickel system exhibits several anomalies with respect to thermal expansion, magnetic and thermoelastic characteristics which are used to advantage in a number of special purpose alloys. Thermal expansion over an appreciable temperature range becomes practically negligible in the vicinity of

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30-60% nickel range to select alloys of appropriate expansivity to fit particular applications. The widest usage of these materials is for the low expansion side of thermostatic bimetal. The high expansion side also is frequently an iron-nickel base alloy with an addition of chromium. A favored composition is 22% nickel and 3% chromium. See page 465 for additional information.

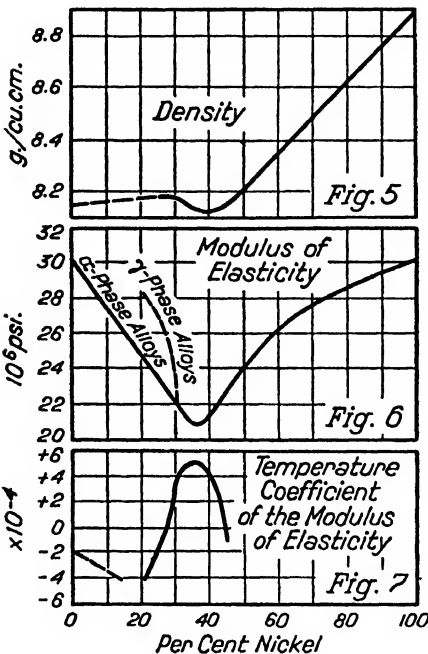


Fig. 5—Density of iron-nickel alloys.

Fig. 6—Variation of modulus of elasticity with nickel content.

Fig. 7—Variation in the temperature coefficient per °C. of the modulus of elasticity with nickel content. (Guillaume, and Keulegan, and Houseman.)

ordinary atmospheric temperatures and therefore shows a variable magnetic permeability in this temperature range. This makes the alloy valuable for temperature compensating shunts in watt meters and other electrical devices. Alloys lower in nickel content are above their magnetic change point at room temperature and therefore nonmagnetic, provided they are fully austenitic. If more than 20% nickel is present, air cooling is sufficiently rapid to suppress the $\gamma - \alpha$ phase change, so that these alloys are useful for applications requiring nonmagnetic metals of good strength, high toughness and favorable corrosion resistance. For reasons of economy, however, it is the usual practice to reduce the nickel content and restore austenite stability through additions of manganese and chromium. The same method is followed in the production of nonmagnetic cast irons, some of which contain copper.

In the range of stable austenitic iron-nickel alloys containing from 35-90% nickel there have been developed a number of alloys possessing extremely useful magnetic characteristics. One of the important properties of these materials is high permeability under the influence of weak magnetic fields making them valuable as loading materials in electrical communication circuits. Continuous loading of transoceanic cables with 78.5% nickel ("Permalloy") strip resulted in speeding up transmission fivefold.

These alloys as a class show high permeability and low hysteresis loss. By varying the percentage of nickel and judicious addition of other elements, such as cobalt, copper, molybdenum, and chromium, various characteristics may be emphasized and different combinations of magnetic properties secured. The latter two

Most metals possess a negative thermal coefficient of the elastic modulus, that is, they lose stiffness with increasing temperature. Iron-nickel alloys with nickel between about 27-44% exhibit a positive coefficient, reaching a rather high maximum at about 36%, which is also the point of minimum thermal expansion. This property is of value for certain temperature compensation applications. Composite springs of steel and 36% nickel-iron can be made to maintain a constant stiffness in the face of temperature fluctuations due to the opposing effects of temperature on the moduli of the two materials.

Replacement of some of the iron in the 36% nickel-iron alloy with chromium progressively lowers the positive thermoelastic coefficient until at some 8-12% chromium it is practically zero. Constant modulus alloys of this type, with additions of certain other elements to improve the elastic limit, are useful for hair springs in timekeeping devices, scale springs, tuning forks, and bourdon tubes.

The austenitic iron-nickel alloys are magnetic at all temperatures below the magnetic transformation point, which temperature varies with composition. In the ferritic condition they will always be magnetic, but in the austenitic condition this will depend on their position with respect to the magnetic transformation curve.

The austenitic 30% nickel alloy is in the magnetic transformation range at

elements are particularly useful in increasing the electrical resistivity, thus reducing eddy current losses.

Thus in the iron-nickel series there exist alloys varying all the way from the completely nonmagnetic to those offering maximum magnetic softness. It was discovered by Mishima in Japan that additions of aluminum to appropriate nickel-iron alloys would produce materials of high magnetic hardness. Such alloys now find extended use for permanent magnets since they provide more magnetic energy per unit of volume than any other permanent magnet material commercially available. They are made in several grades, some containing, in addition to the nickel and aluminum, various combinations of cobalt, titanium, and copper. The nickel content is usually 20-25% and the aluminum 10-15%.

Variations with nickel content of some of the important physical properties of the iron-nickel series are shown in Tables I and II and Fig. 1-7.

Table I
Tensile Properties of Iron-Nickel Alloys

Composition, %			Treatment ¹	Tensile Strength, Psl.	Elastic Limit, Psl.	Elong. in 2 in., %	Reduction of Area, %
Nickel	Manganese	Carbon					
26.0	1.50	0.20	As Rolled	78,500	12,000	50.0	70.7
			Quenched	78,000	15,000	49.5	70.5
30.0	1.50	0.15	As Rolled	90,000	27,000	39.5	69.7
			Annealed	84,500	28,000	46.5	68.5
			Quenched	81,500	23,000	44.2	70.5
30.0	2.00	0.40	As Rolled	105,000	45,000	47.0	66.6
			Annealed	101,500	35,000	46.5	66.4
			Quenched	91,000	25,000	45.7	69.3
32.3	2.30	0.12	As Rolled	82,000	30,000	37.5	65.6
			Annealed	77,500	22,000	43.0	68.2
			Quenched	73,000	18,800	39.5	64.7
35.1	1.50	0.22	As Rolled	89,000	30,000	40.6	67.5
			Annealed	85,000	30,000	42.0	67.3
			Quenched	82,000	27,500	41.0	65.0
36.0	0.50	0.08	As Rolled	76,500	36,500	36.3	65.6
			Annealed	72,500	24,000	39.2	67.5
			Quenched	70,500	20,000	38.0	58.3
43.0	1.50	0.35	Cold Drawn	100,000	52,500	16.2	46.0
45.0	1.50	0.37	As Rolled	107,000	40,000	40.0	51.1
			Annealed	94,500	35,000	43.7	51.1
			Quenched	73,000	19,500	38.0	46.3
50.7	1.25	0.17	As Rolled	99,000	48,500	38.5	67.7

¹Annealed from above 1450°F.
Quenched from above 1400°F.

Table II
Electrical and Thermal Properties of Iron-Nickel Alloys¹

Nickel, %	Temperature Coefficient of Resistance ² 32-212°F.	Thermoelectric Power (against Copper) 32-205°F., Microvolts per °F.	Thermal Conductivity 68-212°F. B.t.u./hr./sq. ft./in./°F.	Specific Heat 77-212°F. B.t.u./lb./°F.
21.0	.0010	13.1	...	.1163
22.1	.0010	11.7	142.0	.1181
25.2	...	...	92.8	...
26.4	.0009	9.3	...	...
28.4	...	...	80.6	.1191
35.1	.0008	5.4	76.0	.1228
40.0	.0012	12.4	...	...
45.0	...	16.1	...	.1196
47.1	.0020	17.7	106.4	.1181
75.1	...	...	200.2	...

Nickel, %	Temperature Coefficient of Resistance ² 0-100°C.	Thermoelectric Power (against Copper) 0-96°C., Microvolts per °C.	Thermal Conductivity 20-100°C., cal./sec./sq. cm./cm./°C.	Specific Heat 25-100°C. cal./g./°C.
21.0	.0018	23.5	...	...
22.1	.0018	21.0	.0490	.1163
25.2	...	...	.0320	.1181
26.4	.0016	16.7	...	...
28.4	...	...	.0278	.1191
35.1	.0011	9.8	.0262	.1228
40.0	.0022	22.4	...	...
45.0	...	29.0	...	...
47.1	.0036	31.9	.0367	.1196
75.1	...	...	.0691	.1181

¹Data from Ingersoll, Physical Rev., v. 16, 1920, p. 126.

²For specific resistance see Fig. 2.

Silicon As An Alloying Element in Steel

By W. E. Ruder*

Physical Constants—The physical constants for the element silicon are given elsewhere in this Handbook.

General—Next to oxygen the element silicon is the chief constituent in the solid crust of the earth, where it occurs as the oxide, SiO_2 , in various forms, such as sand, quartz, flint, opal, or in silicates. It may be obtained as an amorphous powder or in crystalline form by reduction with aluminum, magnesium, or carbon. Pure crystalline silicon in mass has an opaque, metallic appearance. The oxide is acid in its reaction and combines readily at elevated temperatures with most metallic oxides to form silicates.

Source of Silicon in Steel—The silicon content of basic open hearth or Bessemer steel is usually under 0.01%, unless it is added during the finishing period of the heat. Under certain conditions acid open hearth steel may, without the addition of silicon, contain 0.25-0.35% silicon.

The source of silicon in basic steel is from the silicon in the pig iron and scrap used, and in acid steel, from the pig iron, scrap, and acid lining.

The silicon content of pig iron is derived from the reduction of the silica in the ore by coke. The amount of silicon in the iron depends primarily on the temperature and the type of slag used. The approximate silicon content of pig iron is as follows:

Pig Irons	% Silicon
Basic	about 1.00
Bessemer	1.00-2.00
Foundry	1.25-2.75
Scotch	3.00
Silvery	3.00-5.00
Softener	8.00

Ferrosilicons are usually referred to by the silicon content as 10 or 15% silicon pig, 50, 75 or 90% ferrosilicon. Ferrosilicon is usually, and in the higher percentages always, made in the electric furnace. Silico-spiegel is a blast furnace product containing 6-12% silicon and 17-22% manganese. Silico-manganese is an electric furnace product containing from 18-25% silicon and from 60-70% manganese. Most of the silicon introduced into the metal by the pig iron is oxidized during the process of steel making, but more is added at the end of the process to deoxidize and produce a sound product if killed or semikilled steel is desired. Such addition is usually made to the ladle in the form of 50% ferrosilicon. The silicon reduces the iron oxide present to form silica (SiO_2) or complex silicates most of which, if given time, will combine with the slag. The mechanism of its action in producing sound steel, namely, steel free from blowholes, is not definitely known at present. Silicon is a more efficient deoxidizer than manganese, but does not give the beneficial effects that manganese does in the rolling of steel.

The use of an alloy of 4:1 or 7:1 manganese to silicon ratio is finding increasing favor as a deoxidizer for open hearth steels.

Toxic gases, principally phosphine and arsine, are given off by impure ferrosilicon in contact with moist air. Calcium carbide will cause disintegration of ferrosilicon in the presence of moisture.

Critical Points—Silicon has a marked effect upon the critical points. With increasing silicon in low carbon alloys the A_1 point decreases in intensity and disappears entirely at about 2¼% silicon. The magnetic transformation (A_2) is depressed about 9°C. (17°F.) per 1% silicon up to 4%. From 4-15% the rate increases to 22°C. (39.5°F.) for each per cent of silicon added. The closed gamma region extends to 2¼% silicon in very low carbon alloys and to about 5% with 0.2% carbon present.

*General Electric Co., Schenectady.

In high silicon transformer sheets the magnetic transformation (A_s) occurs at approximately 730°C. (1346°F.).

Effect of Silicon on Physical and Mechanical Properties—The *specific volume* increases from 0.128-0.138 at 14% silicon, from 0.138-0.165 at 33% silicon, from 0.165-0.225 at 57%, and from 0.225-0.440 for 100% silicon. The *density* falls off from 7.89-7.5 with added silicon up to 5%. The *specific heat* in the room temperature range is increased from that of iron, 0.102-0.1298 for 10% silicon, 0.1448 for 50% silicon, and 0.1652 for 95% silicon. The *thermal expansion* of iron-silicon alloys decreases with increasing silicon content. Up to 4.5% silicon increases the tensile strength and yield point, but a further increase in silicon causes a rapid decrease. The elongation and reduction of area show little change up to 2.5% silicon, beyond which, however, increased silicon causes these properties to fall off rapidly.

Silicon in Cast Iron—Silicon and carbon are the principal elements affecting the properties of cast iron. Increasing the amount of silicon added to iron results in a progressive reduction of the melting point from 1530°C. (2786°F.) for pure iron to 1205°C. (2201°F.) for 20% silicon. For any given carbon content an increase of silicon from 1-3.5% changes the structure of cast iron from hard brittle white iron successively to mottled, pearlitic, gray, and "open" structure. These structures are further modified by the degree of superheat and by mold temperature used, but the really important influence of silicon on cast iron is its graphitizing effect on the carbides.

Chemical ware castings obtain their resistant properties from the compound Fe_3Si , which contains 14.5% silicon. No increase in resistance to corrosion is observed under 10% silicon. Such castings usually contain 0.5-1.0% carbon, 0.3-0.8% manganese, and sometimes a little nickel.

Silicon in Tool Steel—In carbon tool steels where silicon may be present in percentages from 0.10-0.60%, increase in silicon content is accompanied by an increase in depth of hardness penetration after quenching. In lower carbon alloy tool steels, silicon in percentages from 0.75 up to 2.50% is used in connection with other elements such as manganese, molybdenum, vanadium or chromium to produce an increase in ductility without loss in tensile strength or hardness.

Silicon in Stainless Steels—One-half to 4% of silicon in stainless steels, of the 18-8 type, appreciably increases their resistance to certain types of corrosion and to high temperature oxidation. It retards hardening and tends to increase brittleness in these alloys. A 12-14% chromium stainless iron containing 2% or more of silicon cannot be hardened, except by cold work. Gas engine valve steels are much improved by the addition of silicon. These steels have about 6-9% chromium, 1-4% silicon, and 0.5% carbon. The A_1 point of these steels is rapidly raised by the addition of silicon to 1000°C. (1832°F.) for 3.5% silicon.

Silicon in Structural Steels—Silicon in structural steels is best known as an alloy with manganese for spring steels. A steel of approximately 0.5% carbon, 0.7% manganese, and 2% silicon, oil quenched from 900°C. (1652°F.) and tempered at 455°C. (851°F.) gives excellent strength and toughness and is widely used for leaf and coil springs. Chromium-manganese-silicon, silicon-chromium, and silicon-vanadium steels are also used. A low silicon steel of approximately 0.20-0.40% carbon, 0.60-0.90% manganese and 0.20-0.35% silicon has been a standard for high stressed structural members in this country for a number of years. Recently the Germans have started to manufacture similar steels, using 0.80-1.00% silicon and 0.50% manganese. "F" or Freund Steel contains about 0.12 carbon, 0.40-0.70 manganese, and 0.75-1.50% silicon.

Magnetic Alloys—Silicon increases the electrical resistivity of iron 11.4 microhms per cm. cube for each per cent of silicon added. By decreasing the solubility of ferrite for carbon and by promoting grain growth, silicon decreases the hysteresis loss. These factors are very important in magnetic circuits of electrical machinery, so silicon alloy sheets are used in almost all magnetic circuits where alternating current is used. For the best results all other elements, particularly carbon, oxygen, and sulphur, should be as low as possible. Low silicon (0.75-3.0%) alloys are also excellent for relay cores.

Grades of Electrical Sheets—Electrical sheets, as these magnetic alloys are usually referred to in the industry, are divided into five general classes as referred to below, with standard guarantee losses for three gages most commonly used.

These loss figures are for standard Epstein samples cut half with and half across the rolling direction from annealed sheets.

Electrical sheets are usually made in basic open hearth or electric furnaces. Sheets are usually hot rolled and to be acceptable should be flat, free from loose

Grade	Uses	% Silicon	Loss 60-Cycle 10,000 B Watts per lb.		
			0.014 in. (29 Gage)	0.0187 in. (26 Gage)	0.025 in. (24 Gage)
"Armature"	Generators; small motors	0.5	1.30	1.55	1.98
"Electrical"	Generators; small motors	1.0	1.17	1.35	1.70
"Motor"	Induction motors	2.5-3	1.01	1.14	1.30
"Transformer I"	Generators and low freq. trans.	3.25-4	0.82	0.94	1.10
"Transformer II"	60 cycle transformers	4-5	0.60-0.52	0.74	0.85

or heavy scale, and thoroughly annealed. Silicon increases the brittleness of sheets and for that reason 4% is about the practical limit for structures subject to strain or vibration. For transformers 4.75-5% silicon is commonly used, and for the minimum watt losses and maximum permeability 6.25% silicon sheets are being made. This is the amount of silicon corresponding to zero magnetostriction.

A typical composition of high grade transformer sheet is:

Silicon	4.50-5.00%
Manganese under	0.10%
Phosphorus under	0.02%
Sulphur under	0.02%
Carbon under	0.05%

Carbon, oxygen, and sulphur are considered to be the most injurious of the impurities.

Magnetic alloys in the form of cold rolled strip are finding increased use in the electrical industry. These contain from 0.5-3.5% silicon and are graded the same as sheets. In the thinner strip, that is, under .018 in. and having a high degree of cold reduction, wide differences in quality with rolling direction are noted.

Heat Treatment—The heat treatment of magnetic alloys is governed somewhat by the rolling procedure in that the finished grain size is important. The temperature should be above 800°C. (1475°F.) and should not exceed 900°C. (1650°F.) if any oxidizing conditions are present. The heating and cooling may be as rapid as possible consistent with the achievement of flat sheets, a consideration of first importance. In the lower silicon grades the cooling rate should be slow enough to allow for the precipitation of the carbides as graphite. In the range of 700-500°C. the rate should not be less than about 12°C. per hr. to prevent abnormal brittleness. Electric furnaces are being extensively used for annealing due to the greater ease of control of temperature and atmosphere which they afford.

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Tungsten as an Alloying Element in Steel

By J. L. Gregg*

The Metal Tungsten—Tungsten is a very refractory and heavy metal. Its melting point is 6150°F. and its density approximately $2\frac{1}{2}$ times that of iron. The metal may be obtained in a state of high purity by hydrogen reduction of its oxide, and in such a state it is sufficiently ductile to swage and be drawn into fine wire. Although metallic tungsten is used in electric lamps, X-ray tubes, and in electric contacts it has been estimated that from 95-98% of the tungsten consumed is used in the manufacture of steels.

Tungsten Ores—Metallic tungsten is never found free in nature. The ores from which it is commercially obtained are wolframite and scheelite. Wolframite has the formula $\text{FeMn}(\text{WO}_4)$, varies in composition from FeWO_4 to MnWO_4 , and contains from 60-70% WO_3 . Wolframite containing less than 20% manganese tungstate is called ferbrite and that containing less than 20% iron tungstate is called hubnerite. Scheelite is calcium tungstate (CaWO_4), containing 80.6% WO_3 and 19.4% CaO .

While tungsten minerals are widely distributed over the world, Asia is the largest producer of tungsten ore. In 1936 approximately 70% of the world's output of tungsten was furnished by Asia, most of this ore coming from China and Burma. In some districts of China the ore instead of being mined is gathered from the foot of hills and from streams, where it has been washed by heavy rainfall.

Methods of Adding Tungsten to Steel—Most tungsten steel is made with ferrotungsten, but tungsten can be added to steel by reduction from ore added to the steel making furnace. Ferrotungsten is made by the reduction of tungsten ore, which also contains iron, with either carbon or silicon in the electric furnace. The ordinary ferrotungsten of commerce contains approximately 80% tungsten and less than 0.75% carbon. Practically all of the ferrotungsten used in this country is within the following composition limits:

Tungsten 75-80; carbon 0.40-0.60; phosphorus 0.05; sulphur 0.06; silicon 0.75; manganese 0.80; copper 0.10; arsenic 0.10; antimony 0.05; tin 0.06.

Constitution of Tungsten Steels—Tungsten, like chromium, is a carbide forming element and belongs to that group of elements that tend to suppress the gamma phase of iron. There are two tungsten carbides, WC and W_2C . The former has been detected in steels but not the latter. In the iron-tungsten system there is a compound Fe_3W_2 , which has been observed in low carbon steels, but which probably is rarely formed in commercial tungsten steels, which are mainly steels with a relatively high carbon content. In the ternary system iron-tungsten-carbon there is a compound $\text{Fe}_3\text{W}_2\text{C}$ or $\text{Fe}_3\text{W}_2\text{C}$ and this complex carbide forms in most commercial tungsten steels. There are reasons for believing that this carbide is metastable and that it decomposes to form WC just as cementite in simple iron-carbon alloys decomposes to form graphite. Much of the iron-tungsten-carbon diagram has been worked out, but the apparent diagram is too complicated to permit description in the limited space available here. The findings in regard to the diagram have been reviewed by the author in the book "Alloys of Iron and Tungsten," published in 1934. Also see the article in this Handbook entitled "The Constitution of Iron-Tungsten Alloys."

Tungsten Steels—The preponderant use of tungsten in steels is in tool and die steels. Formerly tungsten magnet steel containing in the neighborhood of 5% tungsten was widely used, but this steel has been superseded by the cheaper chromium steels and the more expensive, but magnetically stronger, cobalt steels and other complex alloys. Some tungsten is used in steels having a high strength at elevated temperatures, usually together with chromium.

Tool and die steels contain as little as 0.5% tungsten, as some oil-hardening, high-carbon steels, and as much as 20% tungsten, as high speed steel. Practically all of these steels contain chromium as well as tungsten. An extensively used steel of the low alloy type is the "fast finishing" steel, used for taking light cuts at high speeds. This type of steel contains from 1.0-1.3% carbon, 1% tungsten, and may contain a fraction of a per cent of chromium and vanadium.

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Table I
Commercial Steels Containing Tungsten and Their Applications

Type Composition, %				Used for
Carbon	Tungsten	Chromium	Vanadium	
0.50-0.65	0.50- 2.00	.....	.....	Chisels.
0.65-0.80	4.50- 7.00	.....	.....	Permanent magnets.
1.00-1.20	1.25- 2.50	.....	.....	Keen edged tools, taps, and chasers.
1.00-1.20	1.00- 2.00	0.50-1.00	.....	Keen edged tools, taps, and chasers.
1.10-1.30	4.50- 6.00	1.00-1.50	.....	For finishing tools, for gun rifling.
0.30-0.45	8.00-11.00	2.50-3.50	0.30-0.60	For hot-working dies and shears.
0.30-0.55	1.50- 2.50	1.25-2.00	0.15-0.40	For hot-working dies, chisels, and punches.
0.50-0.70	1.50- 2.00	0.50-1.00	.....	For valves for gasoline motors.
0.50-0.70	12.00-15.00	3.00-4.00	.....	For valves for gasoline motors.
0.60-0.70	1.00- 3.00	.....	.....	For making gun and Howitzer linings.
0.50-0.80	12.00-20.00	2.50-5.00	0.50-2.25	The very broad analysis of high speed steel, with innumerable uses.
(With or without other elements)				

The high speed steel most widely used in this country contains 18% tungsten, 4% chromium, and 1% vanadium; it is commonly known as the 18-4-1 type. Other types of high speed steels used here contain either more or less tungsten, more vanadium, several per cent of cobalt, or at least part of the tungsten has been replaced by molybdenum. Die steels may contain almost any amount of tungsten up to 20% depending on the service for which they are intended. Compositions of some types of commercial tungsten steels are given in Table I; which was compiled by J. P. Gill of the Vanadium Alloys Steel Co.

Vanadium Steels

By Jerome Strauss* and George L. Norris†

Vanadium—The metallic element vanadium is grayish-white in appearance, nonmagnetic, and has a high electrical resistivity. It is one of the least volatile metals at the melting point. Extremely difficult to reduce to the pure metallic state from its oxides, it is only recently that a purity of 99.7% vanadium has been obtained by Marden and Rich. The metal was malleable and was rolled and drawn into wire.

The physical constants for vanadium are given in the article Physical Constants of the Elements, in this Handbook. No important industrial uses of the pure metal have been developed.

Historical—Vanadium was first discovered in brown lead ore by the Mexican chemist, Del Rio, in 1801. In 1830 the Swedish chemist, Sefstrom, detected it in some remarkably soft, ductile iron produced from an ore at Taberg, Sweden. In 1896 vanadium was first used experimentally in the manufacture of armor plate at the Firminy Steel Works, France. However, it was not until the comprehensive investigation of Arnold in 1900-1901 that vanadium began to receive attention as an alloy for steel. In 1904 Sankey and Smith presented a paper before the British Institute of Mechanical Engineers giving the results of their investigations on chromium-vanadium steels. This paper really marks the beginning of vanadium steel as a commercial product. The discovery within the next year of the large, rich deposit of vanadium ore in Peru immediately made vanadium available in quantities to meet the requirements of the steel industry.

Occurrence and Extraction—Vanadium is one of the most widely distributed of the elements, occurring in small percentages in granites, sedimentary rocks, and clays, and also in many iron, lead and copper ores, bitumens, and petroleum.

The principal sources of vanadium are the minerals patronite, descloizite, cuprodescloizite, mottramite, vanadinite, carnotite, and roscoelite. Patronite is a vanadium sulphide intimately associated with carbonaceous material and occurs in this form, with more or less oxidized modifications, only in the high Andes of Peru. Descloizite, cuprodescloizite and mottramite are vanadates of lead with zinc or copper or both, and are found in commercial quantities in Rhodesia and South West Africa. Vanadinite is a chlorovanadate of lead occurring in the southwestern United States, Transvaal and Spain. Carnotite (a uranyl-potassium vanadate), roscoelite (a vanadium mica) and a vanadium impregnated sandstone often erroneously called roscoelite occur in Colorado and Utah.

Vanadium is reduced from these ores to form ferrovanadium either directly by means of carbon in the electric furnace or from previously prepared vanadium oxide by the silico thermic method in the electric furnace or by the aluminio thermic method without the application of external energy. Vanadium oxide for these reductions and for chemical uses is prepared by roasting ores with sodium compounds to form sodium vanadate followed by precipitation with sulphuric acid from the neutralized vanadate solution.

The compositions of the standard alloys employed in ferrous metallurgy and their methods of use are given in the article Metals and Alloys Used in the Manufacture of Steel in this Handbook.

Production and Price Statistics—In the Table below are recorded the total vanadium content of ores mined throughout the world and the approximate average

Vanadium Production and Price Statistics

Year	World Production of Vanadium in Ores and Concentrates (Metric Tons)	Price of Ferrovanadium in the United States* (Per lb. contained V)
1910	875	\$4.50
1915	1372	2.50
1920	1589	7.00
1925	725	3.30
1930	992 ^a	3.15
1931	661 ^a	3.13
1932	857	2.99
1933	56	2.62
1934	170 ^a	2.80
1935	416 ^a	2.80
1936	975	2.80
1937	1893	2.80

*Excludes ores mined in the United States.

^aApproximate average of all grades throughout year.

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price of the metal in the form of ferrovanadium during the period of major growth of the alloy steel industry. The figures are in most instances approximations due to the difficulty of securing accurate statistics but the trend is shown reasonably well.

Effects of Vanadium in Steel—Vanadium lessens coarse crystallization and grain growth and influences the manner of solution or precipitation of the carbide in or from the solid solution, iron-rich matrix.

The first effect accounts for smaller dendrites in steels as cast, for uniform fine grain size in annealed or normalized, or quenched and tempered steels, without the coarse precipitation of carbide in ferrite known as "abnormality," and for interference with grain coarsening when heating above the temperature range ordinarily employed for heat treatment. The second effect, involving slow solution of the last traces of carbide at heat treatment temperatures accounts for the wide heat treatment range and the benefits it confers, for example, upon articles having both heavy and light sections; it also accounts for the resistance of vanadium steels to tempering and for the occurrence of carbide precipitation at high tempering temperatures. The fine grain size of vanadium steels is conducive to shallow hardening. In some steels this is required, and where uniformity in the hardening depth is important vanadium in small amounts is used to secure this end. When the toughness characteristic of fine grain size is desired along with deeper hardening, other alloying elements are used with vanadium.

Vanadium steels are readily cast, forged or rolled. In machining, these steels are no more severe upon cutting tools than are other alloy steels of equal strength or hardness. Since the grain of vanadium steels coarsens in a narrow range of temperature, only somewhat above the range employed for normalizing or hardening, machining to a smooth surface is readily attainable by such high temperature normalizing. The fine grain and its associated toughness are recovered again after subsequent heat treatment at the usual temperatures.

In tool steels employing large amounts of vanadium the fine grain size is relied upon for toughness at high hardness, while the carbide is effective in producing cutting qualities, abrasion resistance, and permissible high tempering temperatures.

See the article on the Welding of Metals in this Handbook for the welding of vanadium steels.

Constitution of Iron-Vanadium—The Constitution diagram of this binary system, important to a knowledge of the behavior of vanadium steels, will be found on page 403.

Structure of Iron-Carbon-Vanadium Alloys—No recent published data are available for annealed and quenched steels that are sufficiently extensive to yield diagrams similar to those in this Handbook for steels alloyed with manganese, chromium or molybdenum.

Uses and Properties of Carbon-Vanadium Steels—The principal constructional steel of this type has the following composition: C 0.45-0.55, Mn 0.70-0.95, V 0.15 (min.).

This steel is used for locomotive forgings such as axles, crank pins, connecting rods, piston rods. The forgings are usually normalized and tempered.

For automobile crankshafts, this steel is drop forged, normalized, restruck and die straightened at the normalizing temperature and is ready for machining without further heat treatment. These shafts maintain their dimensions without warping throughout machining operations as well as when in service in the motor because of practical freedom from internal stresses.

For large forgings of carbon-vanadium steel the following heat treatment is generally used: Normalize 1600-1650°F., air; temper 1100-1200°F., furnace or air.

The following mechanical properties are typical production values:

	5 in. dia.	9 in. dia.	13 in. dia.
Yield point, psi.....	72,000	65,000	63,000
Tensile strength, psi.....	110,000	97,000	95,000
Elongation, % in 2 in.....	25	24	23
Reduction of area, %.....	52	48	46

This steel responds well to quenching and tempering and has been used for such parts as forging dies, large piston rods, and shafting. Quenched, and tempered from

1000-1200°F., the physical properties obtainable from forgings of over 5 in. section are of the following order: Yield point, 75,000-100,000 psi.; tensile strength, 110,000-130,000 psi.; elongation in 2 in., over 20%; reduction of area, over 48%.

The transformation temperatures of a 0.50% carbon carbon-vanadium steel are:

Beginning	Ac ₁ Maximum	Ac ₃	Ar ₃ Beginning	Beginning	Ar ₁ Maximum
1385°F	1400	1490	1350	1275	1270

Carbon-vanadium steel castings have been used extensively for locomotive and heavy machinery parts such as main frames, driving wheel centers, crossheads, rolling mill coupling boxes, and gears. The following composition is typical: C 0.28-0.42, Si 0.25-0.50, Mn 0.75-1.00, V 0.15 min.

Normalized and tempered carbon-vanadium steel of about 0.35% carbon gave the following values:

Yield Point, psi.	Tensile Strength, psi.	Elong. % in 2 in.	Red. of Area, %	Izod, ft.-lb.
59,900	93,800	23.5	46.3	29.0
55,800	91,000	25.0	44.9	30.8
63,000	90,000	25.0	42.0	35.0*
62,300	93,400	24.5	47.8	20.8

*Double normalized and tempered.

A typical endurance limit based on material of 89,000-90,000 psi. tensile strength is 40,500 psi.

The heat treatments for the development of these properties normalize at 1600-1650°F.; temper 1050-1200°F.; sometimes double normalizing is employed, in which case the temperatures are 1775-1850°F. and 1575-1625°F.

Uses and Properties of Chromium-Vanadium Steels—The chromium-vanadium steels generally conform to S.A.E. specifications (6100 series) which are given in this Handbook under S.A.E. Steels.

S.A.E. Steels 6115, 6120, and 6125—These chromium-vanadium steels, and especially the first two grades, when specified within the carbon range of 0.12-0.20% are used for case hardened parts, such as automobile gears, camshafts, and piston pins. They give a hard, tough, strong case of high wear resisting quality which, due to the low rate of drop in the carbon content as the core is approached, is quite free from the tendency to flaking, powdering, or flowing under pressure.

A frequently used heat treatment procedure is as follows: Carburize at 1650-1700°F. and cool in the pots. Oil quench from 1600-1650°F. Water quench from 1475-1500°F. Temper at 375-425°F.

While this treatment gives the best properties in both case and core, many purposes are served by a single quench, which is carried out directly from the pot or after reheating to 1625°F. Chromium-vanadium steels are more applicable to single quenching than many of the other alloy steels, due to the fine grain in the case, even after the higher temperature necessary for a single quenching operation.

Steels 6120 and 6125 readily respond to cyanide hardening, and are so used for gears, bolts, washers, small stampings, and forgings. The nitrides formed are extremely fine and there is no tendency to develop the long needle-like structure, thus producing case toughness. The transition from the hard surface to the core is not abrupt, and even in long time cyaniding there is no danger of embrittlement of the core.

These chromium-vanadium steels are also used in boiler construction, super-heater tubes, pressure vessels, bolts, tubing for the chemical industry, and for welding rods. Plates and tubing of this steel will have a tensile strength of 80,000-100,000 psi. at room temperature and at 900-950°F. will have double the load-sustaining capacity of carbon steel at the same temperature.

A steel suitable for automotive ring gears and similar parts has the following composition: C 0.12-0.17, Ni 0.40-0.60, Cr 0.45-0.75, V 0.12-0.18. This steel gives freedom from warpage, a fine machine finish, and moderate core strength.

Steels 6125 and 6130—These steels are used for parts requiring high strength and toughness for such parts as automobile axles, steering arms, connecting rods, crankshafts; and for machine tool arbors, spindles, and shafting, and where it is necessary to machine after heat treatment. The following is the general heat treatment of forgings of this composition: Normalize 1600-1650°F., air; quench 1560-1600°F., water or brine; temper 1000-1120°F.

In the heat treated condition forgings have approximately the following properties: Yield point, 115,000-140,000 psi.; tensile strength, 135,000-160,000 psi.; elong. in 2 in., 20-17%; reduction of area, 65-60%; and Brinell hardness, 280-330.

Chromium-vanadium steel containing over 0.35% carbon is generally used in the oil hardened condition. The particular carbon range employed is influenced by the size of the part and the service to be met.

Steels 6135 and 6140—These steels are used in small bevel and spur gears, rocker arms, small tools, wrenches, and other semihard parts. They are also used for large forgings where high elastic strength combined with toughness and fatigue resistance are required, and internal stresses must be minimized such as Diesel engine crankshafts and connecting rods as well as hammer piston rods. For such large forgings, the heat treatment is commonly normalizing followed by tempering from 1000-1250°F.

The following is the general heat treatment for quenched and tempered parts: Normalize 1600-1650°F., air; quench 1560-1650°F., oil; temper, 500-1200°F. according to requirements and size.

The properties are approximately: Yield point, 210,000-75,000 psi.; tensile strength, 225,000-100,000 psi.; elong. in 2 in., 10-25%; reduction of area, 40-60%; and Brinell hardness number, 444-207.

The 6135 type of chromium-vanadium steel, usually with slightly higher chromium, is used for important parts of the equipment for manufacture of synthetic ammonia, notably the large catalyst chambers, because of its resistance to deterioration and ability to withstand high pressures at temperatures up to about 1000°F. This steel is also used for oil cracking stills subjected to high temperatures and pressures and certain types of mild corrosion. These parts, because of their large size, cannot be quenched, but the physical properties and grain refinement are obtained by normalizing and tempering or by annealing. Typical values are as follows:

	Normalized and Tempered	Quenched and Tempered
Yield point, psi.....	63,000- 70,000	75,000- 82,000
Tensile strength, psi.....	93,000-100,000	100,000-110,000
Elongation in 2 in., %.....	24-28	22-25
Reduction of area, %.....	50-56	55-62

Steels 6145 and 6150—These chromium-vanadium steels are used for highly stressed parts such as transmission gears. They have also proven to be ideal for all classes of springs, due to their high elastic limit and fatigue resisting qualities over a wide range of stresses. These steels have been used for many years for automotive chassis springs and valve springs, and are now being extensively used for locomotive and railway car springs. They are also standard for the welding of worn railway rails, providing a tough, wear resistant surface.

For gears and other highly stressed parts, such as shafting, the general heat treatment recommended is: Normalize 1600-1650°F., air; quench 1560-1625°F., oil; temper 450-1050°F. to a Brinell hardness number of 550-320, depending upon requirements.

The properties obtained are approximately:

Yield point, 250,000-125,000 psi.; tensile strength, 270,000-150,000 psi.; elong., 6-17%; reduction of area, 25-50%; and Brinell hardness number, 550-320.

The heat treatment for springs is as follows: Quench 1560-1625°F., oil; temper 850-1025°F. to a Brinell hardness number of 375-444. The properties are approximately: Yield point, 170,000-195,000 psi.; tensile strength, 180,000-215,000 psi.; elong. in 2 in., 14-10%; reduction of area, 40-28%.

The transformation temperatures of some of these chromium-vanadium steels are:

S.A.E. Steel No.	Ac ₁		Ac ₃	Ar ₃	Ar ₁	
	Beginning	Maximum			Beginning	Maximum
6115	1420	1435	1560	1550	1320	1300
6130	1410	1430	1490	1430	1315	1305
6150	1380	1415	1470	....	1305	1290

Uses and Properties of Manganese-Vanadium Steels.—There are three principal steels of this type, one developed primarily for normalized and tempered large forgings, such as locomotive driving axles, crank pins, piston rods, connecting rods and shafts, and similar heavy machinery forgings; the second for rolled plates, structural shapes, engine bolts, and rivets; the third for castings.

Forging—The composition for the forging grade is: C 0.27-0.34, Mn 1.45-1.75, V 0.15 min.

The following heat treatment is general: Normalize 1580-1630°F., air; temper 1150-1250°F., furnace or air.

Typical property values are as follows:

	Yield Point, psi.	Tensile Strength, psi.	Elong., % in 2 in.	Red. of Area, %
Connecting rod	77,800	101,250	28.0	65.6
Crank pin	81,000	104,500	26.0	61.6
Driving axle	74,800	99,000	25.0	59.8

An exceptionally high fatigue or endurance limit is obtained with this grade of steel and a representative value is a 0.55 ratio based on the tensile strength.

Small sections water quenched from 1550-1600°F. and tempered in the range of 500-1200°F. show the following properties: Yield point, psi., 115,000-210,000 psi.; tensile strength, 120,000-235,000 psi.; elong. 23-12% in 2 in.; reduction of area, 65-48%; and Brinell hardness number, 240-475.

The transformation temperatures of this manganese-vanadium composition are:

	Ac ₁		Ac ₃	Ar ₃	Ar ₁	
	Beginning	Maximum			Beginning	Maximum
1340°F.		1360	1420	1320	1125	1090

For the rolled manganese-vanadium steels (plates and shapes), three grades are specified as follows:

	Grade A	Grade B	Grade C
C max. %	0.18	0.18*	0.22
Mn max. %	1.35	1.45	1.55
Si %	0.15-0.30	0.15-0.30	0.15-0.30
P max. %	0.04	0.04	0.04
S max. %	0.05	0.05	0.05
V %	0.08-0.14	0.08-0.14	0.08-0.14
Tensile strength, psi.	70,000-85,000	80,000-95,000	90,000-105,000
Yield point, min., psi., for thicknesses up to 1 in.	50,000	55,000	60,000
Yield point, min., psi., for thicknesses over 1-1½ in.	48,000	53,000	58,000
Yield point, min., psi., for thicknesses over 1½-2 in.	45,000	50,000	55,000
Yield point, min., psi., for thicknesses over 2 in.	42,000	47,000	....
Elongation in 8 in., min., %	20	18	16
Elongation in 2 in., min., % for thicknesses over 1½ in.	28	25	22
Reduction of area, min., %	50	50	40

*0.20% C for sections over 2 in. in thickness.

The transformation temperatures of Grade B manganese-vanadium steel plate are:

	Ac ₁		Ac ₃	Ar ₃	Ar ₁	
	Beginning	Maximum			Beginning	Maximum
1320°F.		1360	1450	1430	1140	1110

Castings—This type is produced in two composition ranges, each containing about 0.10% vanadium. The remainder of the composition closely resembles that used in the common pearlitic or intermediate manganese steel castings. Vanadium produces an improvement in the microstructure and mechanical properties. It retards grain growth at the heat treatment temperatures and is accompanied by an absence of that microsegregation so common to pearlitic manganese cast steels, which is recognized as small martensitic areas under the microscope and productive of low and variable resistance to impact and poor machining qualities. The impact value of these manganese-vanadium steels is from 2-5 times that of similar steels without the vanadium. These cast steels are being used for locomotive and heavy machinery castings in the normalized and tempered condition. The typical compositions are as follows:

C	Si	Mn	V
0.35%	0.40%	1.40%	0.10%
0.30	0.40	1.70	0.10

Typical mechanical properties for the manganese-vanadium cast steels are as follows:

Yield Point, psi.	Tensile Strength, psi.	Elongation, % in 2 in.	Reduction of Area, %	Izod Value, ft.-lb.	
75,500	100,500	27.0	56.2	53.0	Normalized and tempered Double annealed
70,750	103,100	25.0	51.9	43.0	
69,400	93,450	31.0	61.1	61.0	
60,000	96,300	26.8	50.0	28.0	

Endurance limits of 46,000-52,000 psi. have been obtained over the range of tensile strengths giving an endurance ratio of 0.48.

Other Vanadium Steel Castings—While the steels just described are the principal ones produced, there are a number of other alloy steel casting compositions containing vanadium used for more or less special applications. Some of these compositions are as follows:

C	Mn	Si	Cr	Ni	Mo	V
0.30	0.80	0.40	1.00	....	....	0.10
0.30	0.50	0.30	1.00	....	0.15	0.10
0.30	0.60	0.40	0.50	1.30	....	0.10
0.35	1.50	0.40	....	....	0.15	0.10

Vanadium has proved beneficial in retaining shock resistance in copper-bearing steels as is evident from the following table of tests of manganese-copper-vanadium steel:

Composition, %					Heat Treatment, °F.			Yield	Tensile	Elong.	Red. of
C	Mn	Si	Cu	V	All in Air			Point,	Strength,	%	Area,
								psi.	psi.	2 in.	Izod,
											ft.-lb.
0.29	1.12	0.44	1.04	0.10	1650	1500	750	73,200	96,400	30.0	57.0
0.29	1.12	0.44	1.04	0.10	1650	1500	1000	87,000	107,750	26.0	51.9
0.29	1.34	0.50	1.04	0.10	1650	1500	750	69,950	95,050	28.5	55.5
0.29	1.34	0.50	1.04	0.10	1650	1500	1000	85,700	106,700	24.0	48.1
0.16	1.43	0.26	1.15	0.11	1700	1550	750	69,950	90,900	30.0	60.6
0.16	1.43	0.26	1.15	0.11	1700	1550	950	88,150	106,150	24.0	50.6

Ordinary alloy cast steels, when compositions or heat treatment or both are adjusted to produce high hardness and tensile strength, show a rapid decrease in impact value. Many engineers have taken but little cognizance of the impact strength of cast steels even when applied to types of service where high impact value affords a great measure of insurance against failure. The combination of high yield point, high tensile strength, and proportionately high impact resistance

of some harder vanadium cast steels in the normalized and tempered condition are shown in the following tabulation:

Type	C	Mn	Si	Mo	Cr	Cu	V
Mn-Cr-V	0.44	1.48	0.47	....	0.61	....	0.10
Mn-Cu-V	0.43	1.48	0.44	....	....	0.80	0.10
Mn-Mo-V (I)	0.45	1.53	0.48	0.16	....	....	0.10
Mn-Mo-V (II)	0.36	1.17	0.48	0.33	....	....	0.10

Type	Yield Point, psi.	Tensile Strength, psi.	Elongation, % in 2 in.	Reduction of Area, %	Izod Value, ft.-lb.
Mn-Cr-V	76,600	119,250	25.0	56.2	34.5
Mn-Cu-V	85,800	121,200	22.0	46.3	44.5
Mn-Mo-V (I)	83,900	128,900	20.5	35.0	30.3
Mn-Mo-V (II)	90,750	133,450	12.0	25.4	25.5

When design will permit mild quenching (oil), high yield strength and resistance to impact may be obtained in a cast chromium-molybdenum-vanadium steel originally developed for surface hardening by nitrogen. The properties of this steel are as follows:

C	Cr	% Mo	V	Yield Point, psi.	Tensile Strength, psi.	Elong., % in 2 in.	Reduction of Area, %	Izod, ft.-lb.
.19	2.35	0.37	0.27	138,350	152,850	15.0	46.0	40
				119,650	131,900	17.0	65.4	63

Alloy cast steels with higher vanadium content than described possess significant advantages with respect to mechanical properties that make them useful both at normal and at moderately elevated temperatures. In this class, chromium-vanadium, chromium-tungsten-vanadium, and chromium-molybdenum-vanadium steels have proved effective for steel mill rolls, piercing points for seamless tubes, and oil refinery castings.

After normalizing at 1650°F., water quenching from 1500°F. and tempering 650-1250°F., a 1 in. section gave the following properties: Yield point, 90,000-175,000 psi.; tensile strength, 100,000-200,000 psi.; elong. in 2 in. 26-6%; and reduction of area, 57-12%.

The following transformation temperatures are for the 0.35% carbon steel listed above:

Beginning	Ac ₁	Maximum	Ac ₃	Ar ₃	Beginning	Ar ₁	Maximum
1350°F.		1385	1480	1340	1215		1190

Nickel-Vanadium Steel Castings—This steel is used only in the form of castings. A typical composition of nickel-vanadium cast steel is: C 0.28, Mn 1.00, Ni 1.50, and V 0.10. The carbon content is usually in the range of 0.26-0.33%.

After normalizing and tempering, this steel gives the following average properties:

Yield Point, psi.	Tensile Strength, psi.	Elong., % in 2 in.	Red. of Area, %	Izod, ft.-lb.	
68,000	93,850	28.0	53.8	47.8	} Normalized and tempered Double annealed
69,500	98,000	27.5	55.9	55.9	
70,500	96,500	28.0	59.9	59.5	
62,000	95,000	25.0	45.0	40.0	

The endurance limit of this cast steel is typified by a rotating beam method value of 44,000 psi. obtained on coupon bars having a tensile strength of 91,450 psi., thus giving an endurance ratio of 0.482.

One-inch sections quenched from 1500°F. after normalizing at 1775°F. show, over the tempering temperature range of 750-1250°F., the following properties: Yield point, 90,000-120,000 psi.; tensile strength, 100,000-145,000 psi.; elong. in 2 in., 25-14%; reduction of area, 58-43%.

The transformation temperatures for this steel are as follows:

Ac_1		Ac_3	Ar_3	Ar_1	
Beginning	Maximum			Beginning	Maximum
1315°F.	1345	1480	1320	1140	1115

Low temperature impact test results compared with plain carbon steel, are shown in Fig. 1. These tests are on Charpy specimens with keyhole notch and minimum metal section of 5 x 10 mm.

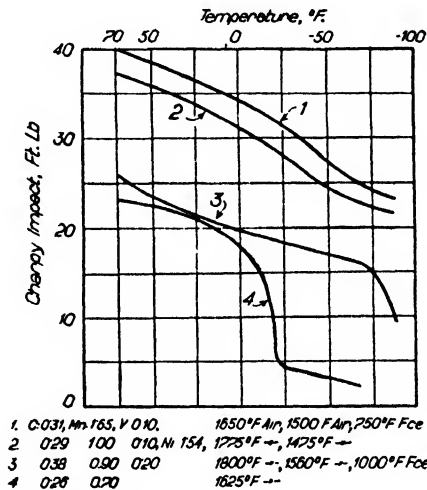


Fig. 1—Effect of temperature on impact strength of vanadium and carbon cast steels.

Uses and Properties of Manganese-Chromium-Vanadium Steel—This steel is used for small forgings such as automobile crankshafts, connecting rods and steering arms. The composition is as follows: C 0.15-0.50, Mn 1.00-1.60, Cr 0.30-0.65, V 0.06-0.12.

One-inch rounds quenched from 1550°F. into water show, over the tempering range of 400-1250°F., the following mechanical properties: Yield point, 95,000-210,000 psi.; tensile strength, 105,000-275,000 psi.; elong. in 2 in., 27-12%; and reduction of area, 65-40%.

An automobile crankshaft in the normalized condition gave the following results: Yield point, 72,000 psi.; tensile 111,000 psi.; elong. in 2 in., 20%; and reduction of area 55%.

The transformations of the manganese-chromium-vanadium steel of 0.40 carbon are:

Ac_1		Ac_3	Ar_3	Ar_1	
Beginning	Maximum			Beginning	Maximum
1360°F.	1380	1510	1345	1240	1230

Silicon-Vanadium Spring Steel—This type of vanadium steel is used principally for helical springs made from bars of ½ in. and over in diameter or thickness, such as railroad car and draft springs. It has high strength properties in tension and torsion, combined with toughness, and good surface condition. As compared with

carbon spring steel, it can be safely worked to about 15% higher stresses without danger of settling.

The composition specification for this steel is: C 0.88-0.98, Mn 0.45-0.65, Si 0.50-0.75, V 0.15 min.

Quenched in oil from 1600°F. (the usual range is 1575-1625°F.) 1 in. rounds, tempered 750-1100°F., gave the following properties: Yield point, 165,000-245,000 psi.; tensile strength, 185,000-270,000 psi.; elong. in 2 in., 14-7%; reduction of area, 35-17%.

Vanadium Nitriding Steels—Vanadium steel parts have been successfully employed in applications requiring the high surface hardness produced by nitrogenous gas at temperatures of 800-1200°F. Vanadium is present in the familiar aluminum-chromium type of nitriding steel in amounts up to about 0.10%.

Alloy steels of the S.A.E. 6100 type, particularly the 0.20 and 0.50 carbon grades, have been used to a limited extent where a maximum surface hardness of 750-800 Vickers suffices. A steel containing approximately 0.25% carbon, 1.50 chromium, and 0.60 vanadium is capable of producing a nitrided case hardness of approximately 850 Vickers. Where higher core hardness and tensile strength with both case ductility and good case hardness are desirable, a steel containing nominally 0.18% carbon, 2.75 chromium, 0.25 vanadium, and 0.50 molybdenum is now available for nitriding, particularly, in the cast condition. A case hardness of 900 Vickers is obtainable with this steel along with good combinations of yield point and impact strength in the core. For higher case hardness, approximately 1050 Vickers, a modification of this chromium-molybdenum-vanadium steel with 4.25% chromium may be employed.

The process has also been applied to a tool steel containing approximately 1.50% carbon, 13.00 chromium, 1.00 vanadium, and 1.00 molybdenum in parts requiring the presence of a hard core (500-600 Brinell) to support the nitrided surface. When quenched from 2050°F. this steel is austenitic, but develops high secondary hardness upon subsequent exposure to a temperature of 950-1050°F. After nitriding, the surface hardness exceeds 1000 Vickers.

Vanadium Tool Steels—Vanadium is an important element in a large number of tool steels. In the low alloy steels the amounts range from 0.15-0.65%, whereas in high speed steel and other high alloy tool steels the quantity usually varies from 0.50-2.50%. In some instances approximately 4% vanadium has been used but at the same time approximately 1.25% carbon has also been introduced.

In the carbon-vanadium steels, the depth of penetration of full hardness is moderate (neither shallow nor deep) and uniform. The vanadium also results in a wider permissible hardening range (for carbon-vanadium steels up to 1600°F.) without likelihood of grain coarsening, thus permitting effective hardening of heavier sections and of tools of variable section without the development of brittleness.

The inclusion of vanadium in the composition of tool steels is generally regarded as productive of stronger and tougher tools that hold their cutting edges better than do tools of steels not containing vanadium.

Details on the heat treatments, compositions, and applications for tool steels and specific classes of tools are given in the heat treating section of this Handbook. As vanadium tool steels are covered, the reader is referred to those articles for additional information.

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Aging in Iron and Steel

By S. Epstein* and H. L. Miller†

Definition of Aging—Aging is the spontaneous change in the properties of iron or steel which occurs at atmospheric temperature, or moderately elevated temperature, after a final heat treatment or final cold working operation. These changes proceed relatively slowly at room temperature but at an accelerated rate as the aging temperature is raised. This indicates that aging is a manifestation of a trend toward equilibrium and away from some unstable condition set up by the final operation performed upon the steel (cooling or cold deformation). Aging may result in an increase in hardness and strength, a loss in ductility and impact resistance, the reappearance after cold working of a sharply defined yield point in the stress-strain curve of a tensile test, an increase in coercive force and similar changes in other properties.

Aging is generally assumed to be caused by the disintegration of a supersaturated solid solution. In a system in which the solid solubility of the solute falls sharply with temperature, the solute may be retained in supersaturated solution by quenching, but it will tend to precipitate out on standing. Such incipient or complete precipitation (more probably incipient) is considered to be the cause of the observed aging phenomena in iron and steel.

Since carbon has a much higher solubility in austenite than in ferrite, the decomposition of austenite to ferrite leads to a precipitation of carbon and to hardening. Indeed, such precipitation may be the chief cause for the high hardness attained by quenched high carbon steel; thus the hardening of carbon steel by quenching may also involve an aging phenomenon. However, the term aging is generally used only with reference to precipitation phenomena in ferrite itself, below the A_1 critical temperature. Such aging occurs in several alloys with iron, as in the iron-copper alloys. However, this article will deal only with aging effects in ordinary iron and steel and not in special iron alloy systems.

Interest in aging has increased since it has become apparent that the "blue heat phenomena" in iron and steel are associated with aging, and since it has been found that virtually nonaging steels can be produced by drastic deoxidation, as with aluminum or titanium, followed by the proper heat treatment.

Hayes and Griffis¹² have reported that the kind of heat treatment which will give a material essentially free from strain aging, consists in heating preferably above the critical range with relatively rapid cooling and then reheating in the neighborhood of the A_1 temperature and slowly cooling. They report they have

found the above heat treatment, when properly carried out, will stabilize materials deoxidized with a wider range of deoxidation treatments than can be produced by slow cooling only, from temperatures either above or below the A_1 point. In general, the less drastic the deoxidation, the more carefully the heat treatment has to be applied to produce a stable material.

Elements Which May Give Rise to Aging Effects—The following elements are found in ordinary iron and steel, C, Mn, Si, P, S, O, and N. Of these, C and N, have an appreciable solubility in ferrite directly below the A_1 temperature and

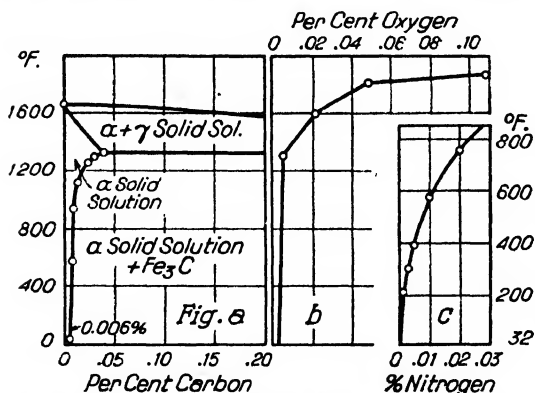


Fig. 1—Change in solubility with temperature of C, O, and N in fairly pure ferrite.^{1, 2, 3}

much lower solubility at room temperature. Thus, if the latter solubility is less than

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the amount of the element present, precipitation and aging phenomena can occur. Curves for the change in solubility with temperature of C, O₂, and N₂ are shown in Fig. 1. All of these solubility curves may be of uncertain accuracy and should therefore be regarded merely as approximations.

Si and P have similar solubility curves, but their solubility in ferrite at room temperature is much higher than that ordinarily present in iron and steel, so that these elements do not give rise to precipitation effects, although they may influence the aging phenomena by causing C, O₂, or N₂ to precipitate out more readily. Mn also has a higher solubility in ferrite than that ordinarily present so it should not of itself give precipitation effects. S is present mainly as MnS inclusions and is not considered to give rise to precipitation effects. However, it is known that MnS has a slight solubility in the solid state and it may therefore have an influence on strain aging.

C and N₂ have been definitely shown to give rise to precipitation or aging effects when present in amounts ordinarily found in low carbon iron and steel.⁹ It will be observed in Fig. 1 that the room temperature solubility of N₂ in ferrite is not more than 0.001%, so that precipitation effects due to N₂ can occur in steel containing more than this amount. Open hearth steel generally contains about 0.004-0.006% N₂, while Bessemer steel may contain over 0.020% N₂; the precipitated N₂ in such steels can be observed under the microscope as nitride needles.

There is still some doubt whether O₂, by itself, is an important cause of aging in iron and steel. Several investigators^{4, 5, 6, 7} have found that iron or steel containing O₂ in amounts such as would ordinarily be found dissolved in such materials, say up to 0.035%, do not show quench aging effects in the absence of C and N₂, although they do show strain aging effects.^{24, 25} Quench aging is the term used to denote the changes which take place in steel following a final operation consisting of fairly rapid cooling from an elevated temperature; strain aging is the term applied to the changes which take place in steel when the final operation consists of cold working; these two categories of aging phenomena will be discussed more fully below. Yensen and Ziegler have reported magnetic aging effects apparently due to O₂ in very pure iron practically free from C and N₂.

This seems to contradict the fact that strongly deoxidized steel is nonaging. The explanation may be that although O₂ does not of itself give rise to aging effects it may cause C and N₂ to do so. That is, O₂ may greatly reduce the solubility of C and N₂ in ferrite so that its presence in solution causes aging. When the O₂ is removed or "fixed" by a strong deoxidizer like Al, however, the room temperature solubility of C and N₂ may be increased thereby and precipitation aging may thus be greatly reduced. Al or Ti would also "fix" the N₂ itself, and Ti would tend to "fix" the C, so that after such strong deoxidation, C and N₂ would not go in and out of solution and hence would not give rise to precipitation effects.

Quench Aging and Overstrain Aging—Overstrain, such as strain above the elastic limit, frequently plays such a prominent part in aging that it has been found convenient to differentiate between aging which results merely from heat treatment and that which occurs after straining or cold working. The former has been designated quench aging and the latter overstrain aging. In overstrain aging a high degree of supersaturation of the solute does not appear to be necessary, but precipitation is thought to occur because overstraining causes local supersaturation along slip planes. In general a steel which shows quench aging will also show strain aging. Low carbon iron, however (C 0.004%), which shows no quench aging still shows overstrain aging effects.⁷

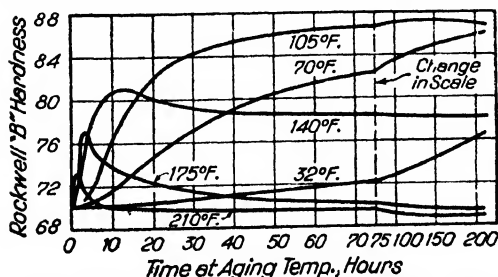


Fig. 2—Quench aging of 0.08% carbon steel. Hardness after quenching from 1325°F. and aging at indicated temperatures³⁰.

room temperature, but the maximum hardness attained is lower. After the maximum hardness is reached further elevated temperature aging causes a decrease in hardness (Fig. 2). This is sometimes called "overaging".

Quench Aging—In quench aging above room temperature the hardness increases more rapidly than at lower temperatures. In general a steel which shows quench aging will also show strain aging. Low carbon iron, however (C 0.004%), which shows no quench aging still shows overstrain aging effects.⁷

Quench Aging—In quench aging above room temperature the hardness increases more rapidly than at

The magnitude of the quench aging effects which may occur in low carbon alloys is illustrated by the following results from Masing and Koch.⁸

C %	Mn %	P %	Si %	Brinell Hardness	
				Directly After Quenching from 1300°F.	On Aging 44 hr. at 125°F. after Quenching
0.028	0.39	0.025	0.003	102	163
0.044	0.44	0.036	0.005	128	185

In a series of Fe-C alloys made up from electrolytic iron without Mn and with 0.02-0.03% P; 0.007-0.008% Si; and under 0.001% S, they obtained the following:

	Carbon, %					
	0.019	0.033	0.043	0.063	0.087	0.166
Brinell Hardness						
Directly after quenching from 1300°F.....	85	79	89	123	127	136
On aging 8 days at 125°F. after quenching.....	92	80	101	207	170	194
Increase in Brinell Hardness.....	7	1	12	84	43	58

No appreciable age hardening occurred in alloys below about 0.035%C. The age hardening effect reached a maximum in the 0.063%C specimen.

The degree of quench aging is greatly reduced by strongly deoxidizing the steel, particularly by killing with aluminum. This is indicated in Fig. 3.

Strain Aging—Straining may result in two effects, first the increase in hardness which accompanies cold working in even the purest single phase metal, and second the increase in hardness by the precipitation or dispersion of another phase induced by the straining. Strain aging is usually determined by measuring the change in hardness (or impact resistance) with time after straining.

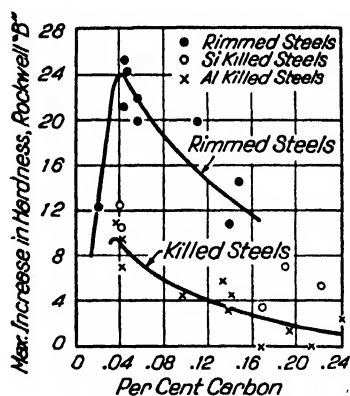


Fig. 3—Reduction in the aging effect as a result of strong deoxidation⁹. The Si killed steel contained about 0.15% Si and the Al killed steel an equal amount of Si with about 0.04% Al. The maximum aging effect occurred at about 0.05%C.

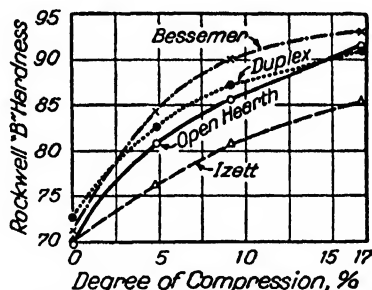


Fig. 4—Increase in hardness with cold work of Bessemer, Duplex, open hearth and Izett steel¹⁰. The first three are aging steels and the last is an Al killed nonaging steel. There was a lower rate of hardness increase with cold work in the nonaging steel.

	C%	Mn%	S%	P%	Si%	Al%
Bessemer	0.08	0.47	0.035	0.102	...	...
Duplex	0.22	0.54	0.030	0.017	...	...
Open	...	...	...	...	...	...
Hearth	0.21	0.40	0.035	0.010	...	...
Izett	0.13	0.58	...	...	0.04	0.05

However, some precipitation may occur during the straining itself. Probably it is for this reason that cold working produces a greater increase in hardness in "aging" than in "nonaging" steels. This is indicated in Fig. 4. No tests were made between 0 and 5% compression. Between 0 and 2% deformation it is frequently observed that no hardening but an actual slight softening takes place. This phenomenon appears to be analogous to a slight softening which is sometimes observed in the early stage of quench aging designated as the incubation period.

In general, the changes in hardness on strain aging are somewhat smaller than on quench aging although the degree of straining influences this to some extent, the greater the degree of straining (within limits) the greater the age hardening. This

is indicated in the following data from Harrison.¹¹ His steel had a composition of C 0.22, Mn 0.37, Si 0.10, S 0.040, and P 0.20%. The Brinell hardness was 118 as annealed from 1700°F.

	As Quenched or Rolled or Both	Aged 2 Months	Increase Hardness Due to Aging	
Quenched in water from 1250°F., Brinell hardness...	151	181	30	Quench aging
Cold rolled 10%, Brinell hardness.....	155	166	11	Strain aging
Quenched in water from 1250°F. and then cold rolled 10%, Brinell hardness.....	183	221	38	Quench and strain aging

On the other hand, the embrittlement induced by strain aging may be greater than that resulting from quench aging. Quench aging lowers the impact resistance but it seldom results in actual brittleness¹ whereas strain aging may result in a brittle fracture. This is indicated in Fig. 5, showing that the impact resistance at room temperature fell to very low values on cold working aging steels (giving brittle fractures) whereas the "nonaging" steel retained high values and a ductile fracture. This is directly after cold working. The impact resistance may be further lowered by aging, particularly accelerated aging, the maximum lowering

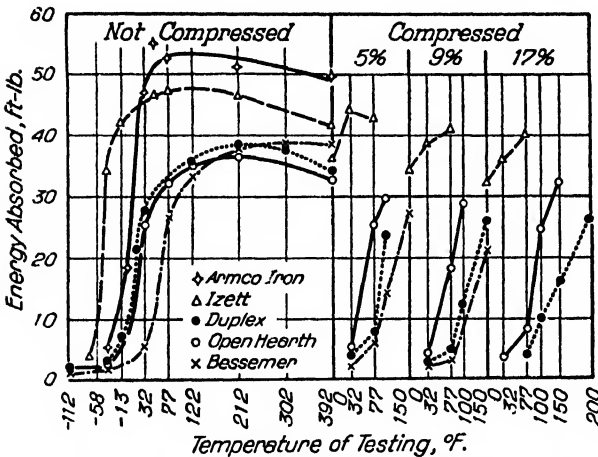


Fig. 5—Effect of cold work on impact resistance of aging and nonaging steels¹⁰. Armco iron, duplex, open hearth, and Bessemer steel are aging; Izett is nonaging.

somewhat ambiguous, but there is no doubt that coarse grained steels are more susceptible to embrittlement (brittle fracture) after straining and aging than fine grained steels.

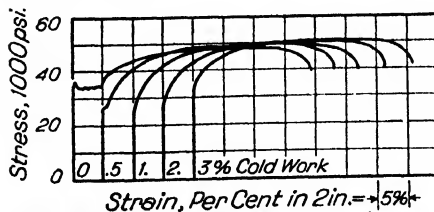


Fig. 6—Jogged stress-strain curve in annealed mild steel sheet¹⁴.

stresses.¹⁴ Hayes and Griffs¹⁵ have recently suggested that the prior cold working may bring the material to a state where the rate of work hardening is high enough to prevent any decrease in load with further deformation.

occurring, on heating about $\frac{1}{2}$ hr. at 500°F.¹² The embrittlement after cold working may be increased on heating a minute or two at 850°F. as in hot dip galvanizing.¹⁰

It should be stated that the relatively nonaging Izett steel in Fig. 5, was finer grained than the others, so that a part of its immunity to embrittlement was probably due to its finer grain. Daniloff¹² has demonstrated that as measured by hardness tests coarse grained steels show greater aging effects both after quenching and aging and after deformation and aging than fine grained steels. As measured by impact tests his results were

A most interesting and not fully understood phenomenon in iron and mild steel is the jog in the stress-strain curve at the yield point which causes the drop in the beam in a tension test. In a previously strained specimen this is not present and a rounded stress-strain curve is obtained instead, with no sharply defined proportional limit. This is shown in Fig. 6. The disappearance of the jog and the rounding of the stress-strain curve have usually been attributed to a loss of elasticity due to the setting up of internal

On aging after cold working the jogged type of stress-strain curve is again obtained in ordinary mild steel such as sheet. In nonaging steel, however, as in the "stabilized" material described by Hayes and Griffis, this does not occur and a rounded curve is still obtained after aging. This is illustrated in Fig. 7.

Fettweiss¹⁷ suggested in 1919 that the increase in tensile strength which is observed in the region of about 400°F. (the blue heat region) is caused by aging, the explanation being that the test specimen increases in hardness due to cold work and aging while it is being deformed in testing. Fettweiss' hypothesis has received striking confirmation in tensile tests of the recently produced Izett type nonaging structural steel and in the stabilized sheet steel, in the blue heat region.^{18, 19} Neither of these nonaging materials showed so pronounced an increase in strength in the blue heat region as aging material. Thus the "blue heat phenomenon" is obviously an aging effect.

Such results by Kenyon on stabilized sheet and on ordinary aging sheet are shown in Fig. 8 and 9. The stepped stress-strain curves of the aging material tested in the blue heat region, as shown in Fig. 9 are characteristic. Kenyon¹⁰ has stated that a tensile test in the blue heat region is one of the simplest ways of distinguishing between aging and nonaging material.

The blue heat region is frequently referred to as the blue brittle region. This term is accurate in so far as the ductility in a tension test at these temperatures is appreciably lower. Likewise after deformation at these temperatures, or on deformation at room temperature followed by heating at those temperatures, there

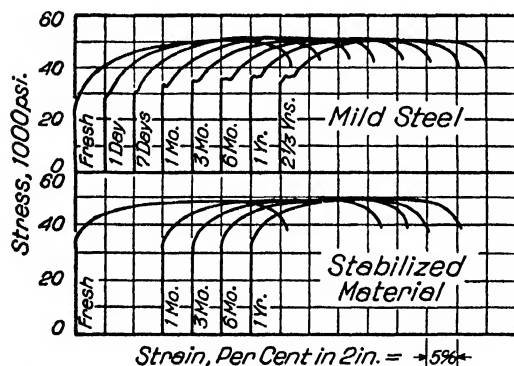


Fig. 7—Return of jogged stress-strain curve on aging after straining in ordinary mild steel. Retention of smooth rounded curve after aging in stabilized or nonaging material¹⁸. Both materials rolled 1% before aging. Typical compositions of stabilized or nonaging material strongly deoxidized with Al and Ti

C%	Mn%	P%	S%	Si%	Ti%	Al%
0.05	0.03	0.005	0.019	.....	0.067	0.042
0.042	0.47	0.011	0.014	0.073	0.058	0.037

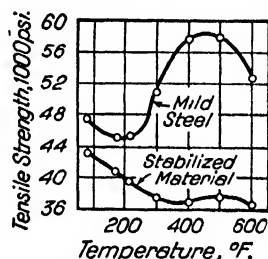


Fig. 8—Effect of testing temperature on tensile strength of ordinary mild steel and of stabilized sheet¹⁰. The stabilized material gives almost no indication of the blue heat phenomenon. The ductility in a tension test of the stabilized material in the blue heat region is considerably higher than of ordinary aging mild steel sheet.

is a marked drop in impact resistance on testing at room temperature. However, there is no brittleness under impact in the ordinarily stated blue heat region at about 400°F. As a matter of fact as indicated in Fig. 5, the impact resistance on testing at these temperatures is nearly at a maximum.

It is true that at temperatures considerably above the blue heat region a minimum in the impact resistance-temperature curve does occur. This is shown in Fig. 10. The minimum is assumed to be due to an aging effect, that is, it is generally held that at the high speed of fracture in a dynamic impact test any aging (hardening) during the instant of fracturing can only occur at the higher temperature at which this reaction takes place rapidly. At lower temperatures, precipitation during a dynamic impact test cannot occur rapidly enough to cause hardening and hence there is no lowering of the impact resistance. There appear to be no data to indicate whether nonaging steel shows a less pronounced minimum in the impact resistance-temperature curve than aging steel.

Oddly enough, at approximately the same temperature as the minimum in the

impact resistance-temperature curve, a minimum in the ductility in a tension test also occurs. This has been termed by Freeman and Quick²¹ as the "secondary low ductile range." The severity of the "secondary low ductility" varies greatly in different steels. Although it appears to be decidedly affected by the manner of deoxidation of the steel, it is rather doubtful that secondary low ductility is mainly a precipitation or aging effect. Shapiro²² has indicated that it may be connected

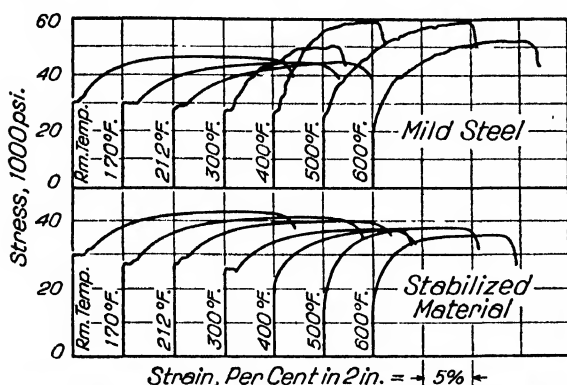


Fig. 9—Stress-strain curves of ordinary mild steel sheet and stabilized sheet tested at various temperatures. The "stepped" stress-strain curve and the higher tensile strength of the ordinary sheet in the blue heat region is characteristic. These features are absent in the stabilized sheet.

which leaves the steel in an ideal condition for strain aging. Unless the material is promptly fabricated, the resulting increase in hardness and corresponding loss in ductility due to aging may constitute the difference between success and failure in the particular application involved.

The jog in the stress-strain curve at the yield point in a tension test manifests itself in the drawing and stamping of sheet as "stretcher strains"²³ giving an undesirable roughening of the surface. The jog is a characteristic of iron and steel in the soft annealed condition and can be eliminated by slight deformation as in the final "skin rolling" given the annealed sheet for this purpose and for straightening.¹⁸ In aging material the jog may return with time so that after leaving the steel mill and storing in the customer's plant the sheet may regain the tendency to stretcher strain. This does not occur in drastically deoxidized nonaging sheet. Such killed steel sheet is also more uniform from edge to center than rimming steel and apparently gives satisfactory drawing properties.

Cold deformation of structural steel, particularly when followed by reheating as in galvanizing, may lead to decided embrittlement. This is much less marked in aluminum killed nonaging steel. The benefits of such steel in overcoming embrittlement become decided only after normalizing, and not in the as rolled condition. Apparently the grain refinement which results from normalizing the fine grained type aluminum killed steel plays an important part in overcoming embrittlement. A punched rivet hole in a thick structural member provides a severe condition which may cause embrittlement even under slow bending.¹⁹

with the rate of recrystallization at this temperature during and after deformation, which rate may, of course, differ according to the degree of deoxidation, grain size, and rate of cooling of the steel.

Practical Aspects—

In practice the effects of strain aging are possibly of greater importance than those of quench aging. This is particularly true in the manufacture of low carbon sheet and strip steel for stamping and deep drawing; the final mill operation on this product is frequently a light "skin pass" or temper rolling

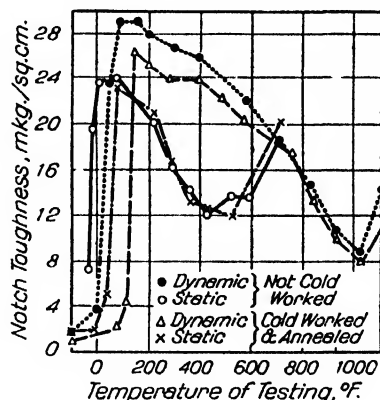


Fig. 10—Static and dynamic notched bar tests at various temperatures with annealed and with cold worked mild steel²⁰. On slow bending the energy absorption is at a minimum in the blue heat region, but in the impact test the minimum in energy absorption occurs at a considerably higher temperature.

In Germany, embrittlement failures in boiler plate have been attributed in part to the aging of strained areas about rivet holes and the use of nonaging steel for boilers has been advocated.¹²

Two probable instances of quench aging in which straining plays no part are temper brittleness, and the galvanizing embrittlement of malleable cast iron.

Temper brittleness is a fall in impact resistance in hardened medium carbon structural steel which occurs if the steel is slowly cooled after tempering but not if it is rapidly cooled after tempering. It was first noticed in nickel-chromium steel but has recently been observed also in carbon steel.¹⁴ Temper brittleness is no doubt a precipitation or aging effect. As with the other aging phenomena, it appears to be less pronounced in strongly deoxidized steel.^{15, 16} Temper brittleness appears to be more pronounced in steel with higher manganese and chromium, while molybdenum is known to reduce it.

Malleable cast iron may be decidedly embrittled by heating to 850°F. as in galvanizing. Marshall¹⁷ has shown that such embrittlement may be overcome by heating the castings to 1200°F. and water quenching, before galvanizing. Although the mechanism of this immunizing treatment is by no means understood,¹⁸ galvanizing embrittlement of malleable iron may perhaps be an aging effect; chemical composition of the iron, particularly the phosphorus and silicon content, also plays an important part in galvanizing embrittlement as shown by Bean.¹⁹

The prolonged annealing and slow cooling of malleable iron may possibly make it more susceptible to subsequent embrittlement by galvanizing. The following data from Harrison¹¹ point to an apparently analogous effect in steel, the more slowly cooled specimen being more susceptible to subsequent embrittlement in quench aging than the more rapidly cooled specimen. Somewhat similarly, in the case of temper brittleness in steel, it has been found that embrittlement occurs even on rapid quenching after tempering (ordinarily in temper brittle steel, embrittlement only occurs on slow cooling from the tempering temperature) if the steel is held for a long time at the tempering temperature.²⁴

Effect of Cooling Rate from 1650°F. Before Quenching from 1250°F.,
on Quench Aging (Harrison¹¹)

Heat Treatment Prior to Quenching in Water from 1250°F.	—Brinell Hardness Numbers—			—Izod Impact Values, ft.-lb.—		
	Tested Immediately After Quenching	Tested After Aging 2 Months	Change	Tested Immediately After Quenching from 1250°F.	Tested After Aging 2 Months	Change
Water quenched from 1650°F..	132	140 + 8		108	97 — 11	
Air cooled from 1650°F.....	130	190 + 60		100	34 — 66	
Slowly cooled in furnace from 1650°F.	124	192 + 68		94	6 — 88	

The galvanizing embrittlement in malleable iron differs from that of the other cases mentioned in that the fracture is intercrystalline.²⁰ Possibly the dispersion effects occur in the grain boundaries as in carbide precipitation in 18-8 stainless steel. Ordinarily in quench aging and strain aging of mild steel the dispersion effects take place throughout the grain and on the slip planes; fracture is mainly transcrystalline.

Aging steels, since they harden and become embrittled more readily under cold work than nonaging steel, machine more easily; the chips become brittle under the action of the cutting tool and break off. For this reason, Bessemer steel makes a freer cutting screw stock than open hearth steel, the higher N₂ and O₂ in Bessemer steel probably promoting aging.²⁰ Because coarser grained steels age more readily than fine grained steels, they machine more readily. In general, fine grain and nonaging characteristics go together, both being caused by strong deoxidation.

Nonaging steels are tougher than aging steels. They have greater damping capacity and Foppl²¹ has indicated that on account of this they are less sensitive to notch effects in fatigue tests below the endurance limit. This is also indicated by the recent work of Brophy.²² Likewise since they do not harden so readily under cold work they are better able to withstand occasional overstresses considerably above the endurance limit, without fatigue failure. That is, they have the ability to withstand considerable cold work and inelastic action without starting a crack. This property has been termed by Moore as "crackless plasticity."²³

Mechanism of Aging—The exact stage of precipitation at which hardening takes place is not clearly understood; it may be complete precipitation of molecules or particles of the excess constituent or a stage between precipitation and solution; the stage of dispersion for maximum hardening may be somewhat different than for maximum embrittlement. Dean¹⁸ in discussing Van Wert's paper has even suggested that blue brittleness is not due to precipitation of iron nitride but to incipient solution.

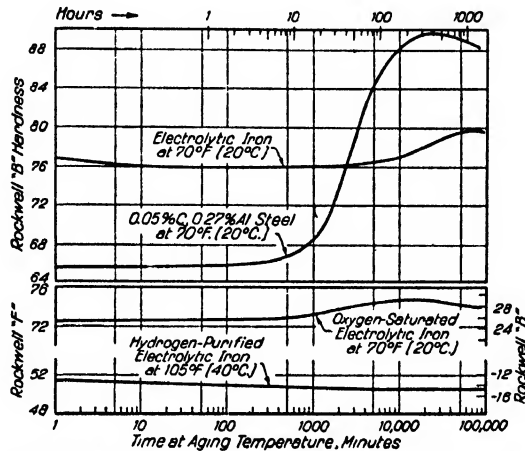


Fig. 11.—Upper block—Quench aging of electrolytic iron and of 0.27% aluminum steel at 70°F. Note wide disparity in degree of age hardening. Lower block—Quench aging of O₂ saturated electrolytic iron at 70°F. and H₂ purified electrolytic iron at 105°F. Note absence of significant age hardening.

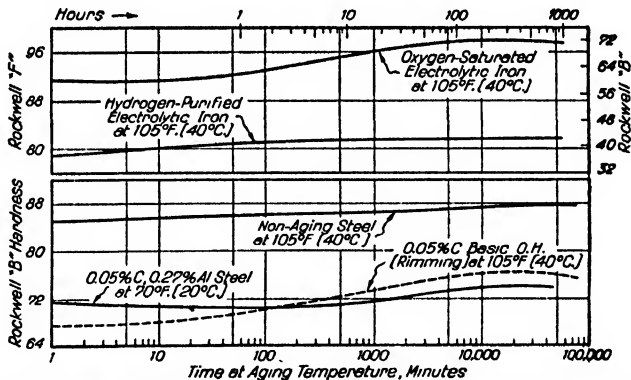


Fig. 12.—Upper block—Hardness of O₂ saturated electrolytic iron and H₂ purified electrolytic iron as strain aged at 105°F. pre-aged before cold deformation. Lower block—Hardness of non-aging steel and rimming basic open hearth steel as strain aged at 105°F.; also 0.27% aluminum steel as strain aged at 70°F. All pre-aged before cold deformation.

As has been stated, there is equal uncertainty as to which element C, O₂, or N₂ is mainly responsible for aging. The fact that drastic deoxidation reduces aging might indicate that O₂ is the main factor. However, in the amounts present in ordinary steel O₂ does not give rise to marked quench aging effects in the absence of C and N₂, although it appears to cause some strain aging effects.^{20, 21} Possibly the part of O₂ in quench aging (somewhat similar to that of P) is to change the solubility of C and possibly of N₂ in ferrite.

In studying the embrittlement of structural steel in galvanizing²² the evidence pointed to N₂, particularly in the presence of P as a cause of aging. Steels in which strain lines can be revealed by Fry etching have been considered more susceptible to aging embrittlement²³ and apparently the strain lines are mainly revealed because of the precipitation of N₂.²⁴ P probably contributes to aging and

embrittlement through its general effect in lowering the impact resistance and in altering the solubility of C and N, in ferrite. Precipitation and aging appear to occur more readily in coarse grain steel, although stretcher strains appear more prominently in fine grain steel. Similarly, it has been observed that precipitation of carbides occurs more readily in coarse grained 18-8 stainless steel than in fine grained 18-8.²⁸

Davenport and Bain²⁹ have recently concluded that quench aging in commercial low carbon steels is mainly due to carbon, while strain aging is mainly due to oxygen. Electrolytic iron high in oxygen and low carbon steel low in oxygen were quench aged as shown in Fig. 11. The effect of the carbon on the hardness is strikingly shown as well as the absence of effect of the oxygen.

Fig. 12 shows the effect of strain aging of low and high oxygen steels as prepared before cold working. The effect of the oxygen content is marked while the carbon seems to have little if any effect on this type of aging.

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S. A. E. Steel Specifications*

A numerical index system is used to identify the compositions of the S.A.E. steels that are partially descriptive of the composition of material covered by such numbers. The first digit indicates the type to which the steel belongs; thus "1-" indicates a carbon steel; "2-" a nickel steel, and "3-" a nickel chromium steel. In the case of the simple alloy steels the second digit generally indicates the approximate percentage of the predominant alloying element. Usually the last two or three digits indicate the average carbon content in "points", or hundredths of 1%. Thus "2340" indicates a nickel steel of approximately 3% nickel (3.25-3.75) and 0.40% carbon (0.35-0.45); and "71360" indicates a tungsten steel of about 13% tungsten (12-15) and 0.60% carbon (0.50-0.70).

In some instances, in order to avoid confusion it has been found necessary to depart from this system of identifying the approximate alloy composition of a steel by varying the second and third digits of the number. An instance of such departure is the steel numbers selected for several of the corrosion and heat resisting alloys.

The basic numerals for the various types of S.A.E. steel are:

Type of Steel	Numerals (and Digits)
Carbon Steels	1xxx
Plain Carbon	10xx
Free Cutting (Screw Stock)	11xx
Free Cutting, Manganese	X13xx
High Manganese	T13xx
Nickel Steels	2xxx
0.50% Nickel	20xx
1.50% Nickel	21xx
3.50% Nickel	23xx
5.00% Nickel	25xx
Nickel Chromium Steels	3xxx
1.25% Nickel, 0.60% Chromium	31xx
1.75% Nickel, 1.00% Chromium	32xx
3.50% Nickel, 1.50% Chromium	33xx
3.00% Nickel, 0.80% Chromium	34xx
Corrosion and Heat Resisting Steels	30xxx
Molybdenum Steels	4xxx
Chromium	41xx
Chromium Nickel	43xx
Nickel	46xx and 48xx
Chromium Steels	5xxx
Low Chromium	51xx
Medium Chromium	52xxx
Corrosion and Heat Resisting	51xxx
Chromium Vanadium Steels	6xxx
Tungsten Steels	7xxx and 7xxx
Silicon Manganese Steels	9xxx

Prefixes

The prefix "X" is used in several instances to denote variations in the range of manganese, sulphur or chromium.

The prefix "T" is used with the Manganese Steels (1300 Series) to avoid confusion with steels of somewhat different manganese range that have been identified by the same numerals but without the prefix.

Carbon Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus Max.	Sulphur Max.
1010	0.05-0.15	0.30-0.60	0.045	0.055
1015	0.10-0.20	0.30-0.60	0.045	0.055
X1015	0.10-0.20	0.70-1.00	0.045	0.055
1020	0.15-0.25	0.30-0.60	0.045	0.055
X1020	0.15-0.25	0.70-1.00	0.045	0.055
1025	0.20-0.30	0.30-0.60	0.045	0.055
X1025	0.20-0.30	0.70-1.00	0.045	0.055
1030	0.25-0.35	0.60-0.90	0.045	0.055
1035	0.30-0.40	0.60-0.90	0.045	0.055
1040	0.35-0.45	0.60-0.90	0.045	0.055
X1040	0.35-0.45	0.40-0.70	0.045	0.055
1045	0.40-0.50	0.60-0.90	0.045	0.055
X1045	0.40-0.50	0.40-0.70	0.045	0.055
1050	0.45-0.55	0.60-0.90	0.045	0.055
X1050	0.45-0.55	0.40-0.70	0.045	0.055
1055	0.50-0.60	0.60-0.90	0.040	0.055
X1055	0.50-0.60	0.90-1.20	0.040	0.055
1060	0.55-0.70	0.60-0.90	0.040	0.055
1065	0.60-0.75	0.60-0.90	0.040	0.055
X1065	0.60-0.75	0.90-1.20	0.040	0.055
1070	0.65-0.80	0.60-0.90	0.040	0.055
1075	0.70-0.85	0.60-0.90	0.040	0.055
1080	0.75-0.90	0.60-0.90	0.040	0.055
1085	0.80-0.95	0.60-0.90	0.040	0.055
1090	0.85-1.00	0.60-0.90	0.040	0.055
1095	0.90-1.05	0.25-0.50	0.040	0.055

Free Cutting Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus Range	Sulphur Range
1112	0.08-0.16	0.60-0.90	0.09-0.13	0.10 -0.20
X1112	0.08-0.16	0.60-0.90	0.09-0.13	0.20 -0.30
1115	0.10-0.20	0.70-1.00	0.045 max.	0.075-0.15
1120	0.15-0.25	0.60-0.90	0.045 max.	0.075-0.15
X1314	0.10-0.20	1.00-1.30	0.045 max.	0.075-0.15
X1315	0.10-0.20	1.30-1.60	0.045 max.	0.075-0.15
X1330	0.25-0.35	1.35-1.65	0.045 max.	0.075-0.15
X1335	0.30-0.40	1.35-1.65	0.045 max.	0.075-0.15
X1340	0.35-0.45	1.35-1.65	0.045 max.	0.075-0.15

Manganese Steels

(See Note (a) for Silicon Content)

S.A.E. No.	Carbon	Manganese	Phosphorus	Sulphur
T1330	0.25-0.35	1.60-1.90	0.040 max.	0.050 max.
T1335	0.30-0.40	1.60-1.90	0.040 max.	0.050 max.
T1340	0.35-0.45	1.60-1.90	0.040 max.	0.050 max.
T1345	0.40-0.50	1.60-1.90	0.040 max.	0.050 max.
T1350	0.45-0.55	1.60-1.90	0.040 max.	0.050 max.

Nickel Steels

See Notes (a) and (b) for Silicon, Phosphorus and Sulphur Content

S.A.E. No.	Carbon	Manganese	Nickel
2015	0.10-0.20	0.30-0.60	0.40-0.60
2115	0.10-0.20	0.30-0.60	1.25-1.75
2315	0.10-0.20	0.30-0.60	3.25-3.75
2320	0.15-0.25	0.30-0.60	3.25-3.75
2330	0.25-0.35	0.50-0.80	3.25-3.75
2335	0.30-0.40	0.50-0.80	3.25-3.75
2340	0.35-0.45	0.60-0.90	3.25-3.75
2345	0.40-0.50	0.60-0.90	3.25-3.75
2350	0.45-0.55	0.60-0.90	3.25-3.75
2515	0.10-0.20	0.30-0.60	4.75-5.25

Nickel-Chromium Steels

See Notes (a) and (b) for Silicon, Phosphorus and Sulphur Content

S.A.E. No.	Carbon	Manganese	Nickel	Chromium
3115	0.10-0.20	0.30-0.60	1.00-1.50	0.45-0.75
3120	0.15-0.25	0.30-0.60	1.00-1.50	0.45-0.75
3125	0.20-0.30	0.50-0.80	1.00-1.50	0.45-0.75
3130	0.25-0.35	0.50-0.80	1.00-1.50	0.45-0.75
3135	0.30-0.40	0.50-0.80	1.00-1.50	0.45-0.75
3140	0.35-0.45	0.60-0.90	1.00-1.50	0.45-0.75
X3140	0.35-0.45	0.60-0.90	1.00-1.50	0.60-0.90
3145	0.40-0.50	0.60-0.90	1.00-1.50	0.45-0.75
3150	0.45-0.55	0.60-0.90	1.00-1.50	0.45-0.75
3215	0.10-0.20	0.30-0.60	1.50-2.00	0.90-1.25
3220	0.15-0.25	0.30-0.60	1.50-2.00	0.90-1.25
3230	0.25-0.35	0.30-0.60	1.50-2.00	0.90-1.25
3240	0.35-0.45	0.30-0.60	1.50-2.00	0.90-1.25
3245	0.40-0.50	0.30-0.60	1.50-2.00	0.90-1.25
3250	0.45-0.55	0.30-0.60	1.50-2.00	0.90-1.25
3312	Max. 0.17	0.30-0.60	3.25-3.75	1.25-1.75
3325	0.20-0.30	0.30-0.60	3.25-3.75	1.25-1.75
3335	0.30-0.40	0.30-0.60	3.25-3.75	1.25-1.75
3340	0.35-0.45	0.30-0.60	3.25-3.75	1.25-1.75
3415	0.10-0.20	0.30-0.60	2.75-3.25	0.60-0.95
3435	0.30-0.40	0.30-0.60	2.75-3.25	0.60-0.95
3450	0.45-0.55	0.30-0.60	2.75-3.25	0.60-0.95

Molybdenum Steels

See Notes (a) and (b) for Silicon, Phosphorus and Sulphur Content

S.A.E. No.	Carbon	Manganese	Chromium	Nickel	Molybdenum
4130	0.25-0.35	0.50-0.80	0.50-0.80	.....	0.15-0.25
X4130	0.25-0.35	0.40-0.60	0.80-1.10	.....	0.15-0.25
4135	0.30-0.40	0.60-0.90	0.80-1.10	.....	0.15-0.25
4140	0.35-0.45	0.60-0.90	0.80-1.10	.....	0.15-0.25
4150	0.45-0.55	0.60-0.90	0.80-1.10	.....	0.15-0.25
4320	0.15-0.25	0.40-0.70	0.30-0.60	1.65-2.00	0.20-0.30
4340	0.35-0.45	0.50-0.80	0.50-0.80	1.50-2.00	0.30-0.40
X4340	0.35-0.45	0.50-0.80	0.60-0.90	1.50-2.00	0.20-0.30
4615	0.10-0.20	0.40-0.70	.....	1.65-2.00	0.20-0.30
4620	0.15-0.25	0.40-0.70	.....	1.65-2.00	0.20-0.30
4640	0.35-0.45	0.50-0.80	.....	1.65-2.00	0.20-0.30
4815	0.10-0.20	0.40-0.60	.....	3.25-3.75	0.20-0.30
4820	0.15-0.25	0.40-0.60	.....	3.25-3.75	0.20-0.30

Chromium Steels

See Note (a) for Silicon Content

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus Max.	Sulphur Max.	Chromium Range
5120	0.15-0.25	0.30-0.60	0.040	0.050	0.60-0.90
5140	0.35-0.45	0.60-0.90	0.040	0.050	0.80-1.10
5150	0.45-0.55	0.60-0.90	0.040	0.050	0.80-1.10
52100	0.95-1.10	0.20-0.50	0.030	0.035	1.20-1.50

Chromium-Vanadium Steels

See Notes (a) and (c) for Silicon, Phosphorus and Sulphur Content

S.A.E. No.	Carbon Range	Manganese Range	Chromium Range	Vanadium	
				Minimum	Desired
6115	0.10-0.20	0.30-0.60	0.80-1.10	0.15	0.18
6120	0.15-0.25	0.30-0.60	0.80-1.10	0.15	0.18
6125	0.20-0.30	0.60-0.90	0.80-1.10	0.15	0.18
6130	0.25-0.35	0.60-0.90	0.80-1.10	0.15	0.18
6135	0.30-0.40	0.60-0.90	0.80-1.10	0.15	0.18
6140	0.35-0.45	0.60-0.90	0.80-1.10	0.15	0.18
6145	0.40-0.50	0.60-0.90	0.80-1.10	0.15	0.18
6150	0.45-0.55	0.60-0.90	0.80-1.10	0.15	0.18
6195(c)	0.90-1.05	0.20-0.45	0.80-1.10	0.15	0.18

Tungsten Steels

See Notes (a) and (d) for Silicon, Phosphorus and Sulphur Content

No.	Carbon	Manganese	Chromium	Tungsten
71360	0.50-0.70	0.30 max.	3.00-4.00	12.00-15.00
71660	0.50-0.70	0.30 max.	3.00-4.00	15.00-18.00
7260	0.50-0.70	0.30 max.	0.50-1.00	1.50- 2.00

Silicon-Manganese Steels

See Note (b) for Phosphorus and Sulphur Content

No.	Carbon	Manganese	Silicon
9255	0.50-0.60	0.60-0.90	1.80-2.20
9260	0.55-0.65	0.60-0.90	1.80-2.20

Corrosion and Heat Resisting Alloys

See Note (e) for Silicon, Phosphorus and Sulphur Content

No.	Carbon	Manganese	Chromium	Nickel
30905	0.08 max.	0.20-0.70	17.00-20.00	8.00-10.00
30915	0.09-0.20	0.20-0.70	17.00-20.00	8.00-10.00
51210	0.12 max.	0.60 max.	11.50-13.00	.....
X51410	0.12 max.	0.60 max.	13.00-15.00	.....
51335	0.25-0.40	0.60 max.	12.00-14.00	.....
51510	0.12 max.	0.60 max.	14.00-16.00	.....
51710	0.12 max.	0.60 max.	16.00-18.00	.....

Notes for Tables of Chemical Composition

Note (a). Silicon range of all S.A.E. basic open hearth alloy steels shall be 0.15-0.30%. For electric furnace alloy steels and acid open hearth alloy steels, the silicon content shall be 0.15% min.

Note (b). Phosphorus and sulphur in all S.A.E. nickel steels, nickel-chromium steels, molybdenum steels and silicon-manganese steels shall be 0.040% max. and 0.050% max. respectively.

Note (c). Phosphorus in all S.A.E. chromium-vanadium steels shall be 0.040% max. except in No. 6195, which shall be 0.030% max. Sulphur in all S.A.E. chromium-vanadium steels shall be 0.050% max. except in No. 6195, which shall be 0.035% max.

Note (d). Phosphorus and sulphur in all S.A.E. tungsten steels shall be 0.035% and 0.040% max. respectively.

Note (e). Silicon shall be 0.50% max. except in alloys 30905 and 30915, which may be 0.75% max. Phosphorus shall be 0.030% max. in all corrosion and heat resisting alloys. Sulphur shall be 0.030% max. in all except in the free cutting alloy X51410, which shall be in the range 0.15-0.30%.

Stainless Steel Type Numbers and Analyses

(Revised Mar. 15, 1938)

Type No.	Carbon	Chromium	Nickel	Other Elements
301X	.10-.20	16.00-17.50	7.00- 8.50	
*302	Over .08-.20	17.50-19.00	8.00- 9.00	
302B	Over .08-.20	17.50-19.00	8.00- 9.00	Si 2.00-3.00
*303	.20 Max.	17.50-19.00	8.00- 9.00	S or Se .07 Min or Mo .60 Max
x304	.08 Max.	17.50-19.00	8.00- 9.00	
*305	Over .08-.20	18.00-20.00	9.00-10.00	
x306	.08 Max.	18.00-20.00	9.00-10.00	
*307	Over .08-.20	20.00-22.00	10.00-12.00	
x308	.08 Max.	20.00-22.00	10.00-12.00	
309	.20 Max.	22.00-26.00	12.00-14.00	
310	.25 Max.	24.00-26.00	19.00-21.00	
311	.25 Max.	19.00-21.00	24.00-26.00	
312	.25 Max.	27.00-31.00	8.00-10.00	
315	.15 Max.	17.00-19.00	7.00- 9.50	Cu 1.00-1.50 Mo 1.00-1.50 Mo 2.00-3.00 Mo 3.00-4.00 Ti Min 4 x C Cu 1.00-1.50
x316	.10 Max.	16.00-18.00	14.00 Max.	
317	.10 Max.	18.00-20.00	14.00 Max.	
321	.10 Max.	17.00-20.00	7.00-10.00	
325	.25 Max.	7.00-10.00	19.00-23.00	
327	.25 Max.	25.00-30.00	3.00- 5.00	
329	.10 Max.	25.00-30.00	3.00- 5.00	Mo 1.00-1.50
330	.25 Max.	14.00-16.00	33.00-36.00	
343	Over .25	12.00-16.00	12.00-16.00	W 3.00 Cb 10 x C
347	.10 Max.	17.00-20.00	8.00-12.00	Turbine Quality
403	.12 Max.	11.50-13.00		Al .10-.20
405	.08 Max.	11.50-13.50		Al 4.00-4.50
406	.12 Max.	12.00-14.00		
410	.12 Max.	10.00-13.50		
414	.12 Max.	10.00-13.50	2.00 Max.	
416	.12 Max.	12.00-14.00		S or Se .07 Min or Mo .60 Max
418	.12 Max.	12.00-14.00		W 2.50-3.50
420	Over .12	12.00-14.00		
420F	Over .12	12.00-14.00		S or Se .07 Min or Mo .60 Max
430	.12 Max.	14.00-18.00		
430F	.12 Max.	14.00-18.00		S or Se .07 Min or Mo .60 Max
431	.15 Max.	14.00-18.00	2.00 Max.	
434A	.12 Max.	14.00-18.00		Si 1.00 Cu 1.00
438	.12 Max.	16.00-18.00		W 2.50-3.50
439	.50-.65	8.00		W 8.00
440	Over .12	14.00-18.00		
441	Over .15	14.00-18.00	2.00 Max.	
442	.35 Max.	18.00-23.00		
446	.35 Max.	23.00-30.00		
501	Over .10	4.00- 6.00		
502	.10 Max.	4.00- 6.00		

*No specified composition limits within the above ranges may be placed on these Types, except carbon may be specified to a four point range within the above limits.

Where definite carbon content .11 or under is specified for Types 302, 305 and 307, the price of Types 304, 306 and 308 respectively apply.

xIn these types manufacturers may accept specifications and furnish material with a guaranteed carbon content of .08 maximum.

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Cast Iron

By Hyman Bornstein* and J. W. Bolton†

I—Definitions and Commercial Classification—Cast irons are alloys of iron containing so much carbon that, as cast, they usually are not appreciably malleable at any temperature. (See below the paragraph on "Graphitic Steels".) Usually from 1.7-4.5% carbon is present and in most cases an important percentage of silicon. Because of the low melting point, fluidity, and simplicity of melting and casting practices, cast irons are readily made into useful shapes through casting processes and by machine cutting operations.

All cast irons are eutectiferous alloys and are classified as follows:

1. Pig iron
2. White cast iron
3. Malleable cast iron
4. Gray cast iron

Pig Iron—Pig iron is the product of the blast furnace and is made by the reduction of iron ore. With the exception of direct metal, pig iron is either remelted and cast (producing gray and white irons), or it is refined in the steel making processes.

(Some special pig irons are blast furnace products diluted in carbon and silicon content by the addition of molten steel to the molten blast furnace product.)

White Cast Iron—White cast iron contains carbon in the combined form. The presence of cementite or iron carbide (Fe_3C) makes this metal hard and brittle. White iron may be further classed according to the process. Chilled white cast iron is produced by casting the iron against metal chills. Such iron when cast in a sand mold may be gray iron, but the chills cause rapid cooling, thus forming cementite. White cast iron for malleable irons may be produced by adjusting the composition; a low silicon and carbon content produces a white or cementite fracture.

Beside chilled irons and white irons for malleable cast iron manufacture, irons white throughout as cast are used for special purposes, particularly for resistance to wear and abrasion. To get maximum hardness, alloys are usually incorporated—both to promote the formation of the cementite and to increase the hardness of the matrix. (See Section VII, Alloy Cast Irons, p. 626.) Special white iron rods are used for welding white iron layers onto various ferrous metals. The very high (25% and up) chromium cast irons, used for their corrosion resistance are white irons, properly speaking,

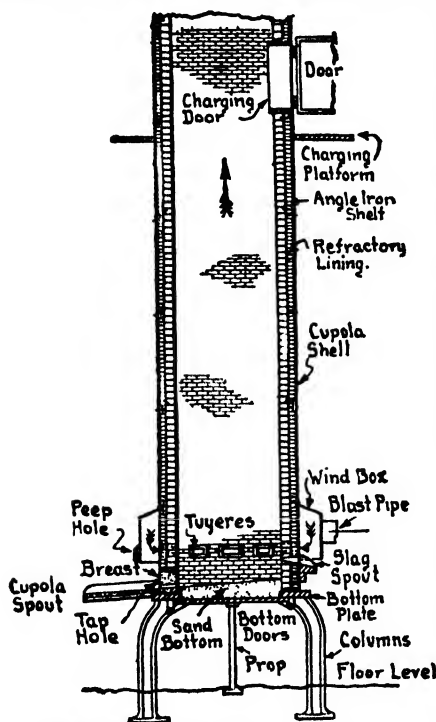


Fig. 1—Sectional view of a cupola (Dr. Moldenke).

but are little harder than some gray irons.

Malleable Cast Iron—This term is applied to castings in which all the combined carbon in a special white cast iron has been changed to free or temper carbon (or temper graphite) by suitable heat treatment. See the article in this Handbook on "Malleable Cast Iron."

Gray Cast Iron—Gray cast irons are cast irons which as cast have combined or cementitic carbon not in excess of an eutectoid percentage—the balance of the carbon occurring as graphite flakes. The term "gray iron" is derived from the characteristic gray fracture of this metal.

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The great majority of castings designated as cast iron castings are gray iron castings. Excellent casting properties, ready machinability, and a wide range of strengths from which selection can be made together with other useful properties, promote good ultimate economy and explain the wide useage of this material where high dynamic stress resistance and high shock resistance are not governing factors in selection.

Gray cast irons are alloys of iron, carbon and silicon. Alloys (such as nickel, chromium, molybdenum) may be added to modify and sometimes to enhance desirable properties. Matrix structure usually is largely pearlitic. By suitable heat treatments, by alloy additions and by other means, various other matrix structures can be produced—ferrite, martensite, or austenite—as may be desired.

Semisteel—The term semisteel is now obsolete and is no guarantee of any specific and useful property in the metal.

Pearlitic Irons—Pearlitic iron is cast iron with a pearlitic matrix. So defined, any iron containing from 0.60-0.90% combined carbon is a pearlitic iron.

High Strength Iron—The term high strength iron has no definite meaning—in some circles it indicates metal over 40,000 psi. tensile strength, while some metallurgists regard only metal over 50,000 psi. tensile as high strength cast iron. In description and specification the specific class intended should be designated. (See Section IX, Classification of Gray Cast Irons.)

Austenitic Cast Irons—These are gray cast irons containing sufficient and suitable alloy content to lower the eutectoid transformation temperature below atmospheric temperatures. This results in retention of an austenitic matrix, with graphite flakes dispersed throughout. Nickel is the commonly used alloy for this purpose. Copper, chromium and molybdenum may be used to abet the action of nickel, or to modify the properties of both. Austenitic cast irons possess unusual magnetic and corrosion resistance properties. (See Section VII and XIII).

Graphitic Steels—An ultimate stable state in the iron carbon alloys (including both steels and cast irons) is reached when all the carbon occurs as graphite. That means by suitable choice of treatment and composition the carbide of any carbon alloy apparently can be graphitized. The fundamental definition of a cast iron is "an eutectiferous alloy of iron and carbon". In pure iron carbon alloys that region above 1.7% carbon is within the eutectiferous range. Various additions (notably of silicon) shift the eutectic concentration. For example, with 2.0% silicon the lower limit of the cast irons is somewhere around 1.1% carbon. Whether an alloy is a true graphitic steel or a special cast iron can be ascertained by application of the principle cited above. It may be noted that some of the lower carbon white irons (approaching the steel series) have appreciable malleability at temperatures well above the eutectoid and that cast irons and graphitic steels (when graphite is in nodular form) have definite ductility.

Alloy Cast Iron—The term alloy cast iron is used to designate irons to which alloying elements, such as nickel, chromium, and molybdenum have been purposely added.

II—Manufacture and Uses of Cast Iron

Gray Iron (Cupola Practice)—The major portion of the gray iron produced in this country is melted in the cupola furnace. The cupola is a vertical, cylindrical type of furnace consisting of a steel shell lined with fire brick (Fig. 1). The furnace is charged through a charging door which is located 15-20 ft. above the bottom plate. At the lower end of the furnace is the wind box, or air chamber, as shown in the diagram. Air enters the cupola through the tuyeres. The cupola is a simple and an economical melting unit because the fuel and the metal are in intimate contact with each other.

Fuel, metal, and flux are charged through the charging door of the cupola. Coke is charged first and the initial charge is known as the bed charge. Iron is then charged upon the coke. Alternate layers or charges of coke and iron are introduced into the cupola. Where flux is used it is charged on the coke. The coke bed is ignited by means of kindling wood or an oil torch. The bed charge or coke usually extends from 28-50 in. above the top of the tuyeres.

The charge of iron depends upon the capacity of the cupola. The cupola sizes are referred to as the inside diameter of the lining of the cupola. Cupolas may range in size from 18 in. dia. inside the lining to over 100 in. The size used for ordinary commercial practice varies from 42-84 in. in dia. The rated capacities on these sizes are from 5-25 tons of metal melted per hour.

The amount of metal charged into the cupola varies considerably, due to local conditions and opinion. Following are sizes of charges which are used in some foundries for various size cupolas:

48 in.....	1500 lb.
60 in.....	3000 lb.
72 in.....	3000 lb.

The size of charges may vary considerably from the figures given, but still be considered good practice.

The quantity of coke used depends upon the quantity of metal charged. The bed charge is a definite height above the tuyeres. Consequently, this portion of the coke goes in by volume instead of by weight. The succeeding charges of coke are in direct proportion to the metal charged. This proportion varies from one part of coke to 7-12 parts of iron.

The metal charged into the cupola consists of gray iron scrap and pig iron. Steel scrap is also used where strength of the finished casting is important. The proportions of gray iron scrap, pig iron, and steel scrap are governed by the type of castings. It is customary to find considerable difference in mixture of metal used, even among foundries making the same class of work.

Limestone is used as a flux in cupola operation. The purpose of the flux is to form a slag with the dirt, impurities in the metal, and the coke ash. Fluorspar (calcium fluoride) is sometimes used as a fluxing agent in combination with the limestone. The purpose of the fluorspar is to thin the slag and also to aid in the removal of sulphur, although correct proportions of limestone will insure a fluid slag and some sulphur removal. Various forms of soda ash are used as fluxes, particularly in the ladle. Intelligent slagging improves the quality of the iron.

The air is introduced into the cupola through the tuyeres. The volume of air introduced is important and governs the melting rate of the cupola. The air is used in the combustion of the coke, which in turn melts the iron. In most foundries about 30,000 cu.ft. of air are used to melt 1 ton of iron. If this figure is greatly exceeded there is a possibility of wild iron, due to excess air. Under ordinary conditions the blast pressure will vary from 8-20 oz., depending on the cupola height, number of charges, and character of charged stock. Some of the larger production foundries have increased blast pressure, in order to obtain greater capacity from the cupola, so that blast pressures in the neighborhood of 30 oz. are used.

Devices are available which permit control of the weight of air entering the cupola. This method is more accurate from the standpoint of control than is the measurement of the air volume.

The metal mixture entering the cupola is governed by the composition of the metal desired for the finished castings. Pig iron is the base of the charge. Charges are seldom made up entirely of scrap. Since the pig iron is of known composition, the greater the amount of pig iron and the smaller the amount of purchased scrap, the more uniform will be the composition of the resulting castings. For high grade castings such as automobile cylinders, the percentage of pig iron is about 35-45% of the charge, while for castings such as sash weights practically no pig iron will be used.

Summary of Cupola Furnace Data for Gray Iron—The following figures are given for normal operations of a cupola. Cupola practice varies considerably, and consequently the figures shown are only given as a guide. Wider limits beyond these figures may be used, and may still be consistent with good practice.

Area of melting zone of cupola in square inches multiplied by 0.75 gives a suitable weight in pounds for iron charge.

One pound of coke is required to melt 8 lb. of iron, figuring coke both in bed and between charges.

125 cu.ft. of air are needed to burn 1 lb. of ordinary coke to carbon dioxide.

Approximately 30,000 cu.ft. of air are required per ton of metal melted.

Melting 8 lb. of iron per sq.in. of cupola area per hour is considered a normal melting rate.

Tuyere area for a 36 in. cupola may be $\frac{1}{4}$ the cupola area and for an 84 in. cupola it may be $\frac{1}{10}$, with other sizes in proportion.

Electric Furnace Melting—During the past few years there has been a steady increase in the utilization of electric furnace melting for cast iron. This is particularly true in the production of special cast irons. The electric furnace lends itself to a high degree of control in respect to composition and temperature. In some cases, large quantities of scrap, such as borings, can be utilized and a good

grade of castings produced. The lower cost of scrap metals for the electric furnaces helps to compensate for the excess melting cost as compared to the cupola.

Two types of electric furnaces are in general use: (a) Three-phase direct arc, and (b) single phase indirect arc of the rocking type. Good results are reported from both types of furnaces.

In some cases the electric furnace is used for the entire melting process while in other cases a duplex method is used. In the duplex method all or part of the charge is melted in the cupola and the molten metal is refined and superheated in the electric furnace. Additions of alloys and steel may be made to the metal in the electric furnace. For steady production the duplex method is usually more economical, due to the low melting cost in the cupola.

Air Furnace Melting—The air furnace (see article on Malleable Cast Iron) is used to a limited extent in the production of gray iron castings. It is frequently used for the higher strength cast irons. The air furnace lends itself to accurate control of composition and higher pouring temperatures are obtained than with the cupola.

Horizontal rotary furnaces (cylindrical in shape) fired with pulverized coal or oil are used to a considerable extent in Europe. Two well known furnaces of this type are the Brackelsberg and Sesci. The furnaces lend themselves to a good degree of control of composition and temperature. The use of these furnaces in the United States was small until about five years ago. During the past five years a number of these furnaces have been installed for gray iron, special white iron, and white iron for malleable castings.

Uses—Gray iron castings are used for a large variety of articles varying in weight from a fraction of a pound to several hundred pounds. A few of these uses are automobile cylinders and pistons, locomotive cylinders, agricultural machinery, machine tool castings, stove castings, car wheels, dies, engine frames and beds, flywheels, water pipe, soil pipe, and hardware.

III—White and Chilled Irons—White cast irons contain practically all their carbon in the combined form, largely as free cementite (Fe_3C) and as pearlite or one of its transition forms. The presence of a large amount of cementite makes the material quite hard and brittle.

White cast iron, to be used as such, usually is produced by proper adjustment of composition. Low silicon content usually is required. Carbide stabilizing elements such as chromium may be added. For methods used in producing white irons in the malleable industry, see the article in this Handbook on "Malleable Cast Iron."

Completely white irons (plain carbon) have comparatively few engineering applications because of their usual brittleness. White iron surfaces on castings are desirable for combating certain types of abrasive wear. It is possible to produce castings with hard white iron exteriors and tough, strong gray iron cores. These castings, usually called chilled castings, may be produced in two ways: (a) By composition adjustment, and (b) by quick cooling by metal "chills." The first method is frequently employed when all the casting surface is required to be chilled. The second method is used to produce localized hardness.

In the first method the desired depth of chill may be obtained by the adjustment of silicon and carbon and other elements. With composition the same, the depth of chill depends largely on the cooling rate, hence larger sections will show less depth of chill than smaller ones.

In the second method the depth of chill depends not only on the composition and thickness of the casting, but also on the heat conductivity of the chills. This depends on the conductivity of the metal in the chill (usually cast iron), its initial temperature, and its thickness. It may be pointed out that irons chilled by chill blocks are of such composition that they would be gray in fracture if cast into sand molds with equivalent section sizes. The hardness of the chill surface and the strength of the gray core can be increased by proper alloy additions.

Among the more common chilled and white iron castings are plow shares, chilled rolls, chilled car wheels, balls, stamp shoes, dies, and wearing plates of various sorts.

IV—Physical Constants* and Mechanical Properties

Transformation Ranges—The values given for transformation ranges are those determined by means of thermal phenomena exhibited on slow cooling.

- (1) The initial solidification point varies with the composition, and is lowered by an increase in carbon and silicon content. It may be as low as about 2066° in an iron of eutectic composition, and as high as about 2500°F. in a white iron containing 2.00% carbon and 0.85% silicon.
- (2) The "Final" solidification, or eutectic solidification, occurs at 2066-2102°F., according to the composition of the metal.
- (3) Steadite formation occurs at about 1750-1800°F.
- (4) Transformation of austenite (nonmagnetic) to pearlite (magnetic) occurs at about 1325-1350°F. in most slowly cooled commercial irons.

Contraction and Expansion—Patternmaker's rules allow $\frac{1}{8}$ in. per ft. for linear contraction of gray iron, and $\frac{1}{4}$ in. per ft. for white iron ($\frac{1}{8}$ in. per ft. is about 1%). This often is found inaccurate in practice, and due allowance must be made for mass, composition, effects of shape, mold, and core. Generally speaking, contraction lessens with increase in mass and increases with increase (in gray irons) in tensile strength.

Three contraction phenomena are exhibited during the cooling of a cast iron from molten state to room temperature: (a) In the liquid, (b) during solidification, and (c) subsequent to solidification. This is shown by the charts by Ash and Saeger, Fig. 2 and 3. These investigators found total linear contractions (2102°F. to room temperature) of about 0.67% for a highly ferritic gray iron to about 1.10% for irons of approximately pearlitic matrix. Typical white irons showed about 2.0% total linear contraction over the same temperature range. In all cases a slight expansion was noted at 1958°F.

Volume shrinkage during solidification ranged from negative shrinkage in "soft" irons to 1.94% in an iron containing about 0.90% combined carbon. The white irons had 4.0-5.5% volume contraction in the same range.

Coefficient of Expansion—The coefficient of expansion of gray irons in the range 0-500°C. (32-932°F.) is about 13×10^{-6} per °C. The expansion is about 10.5×10^{-6} per °C. in the range 0-100°C. (32-212°F.). The expansion varies somewhat with the type of iron and is somewhat higher in the softer and higher carbon irons.

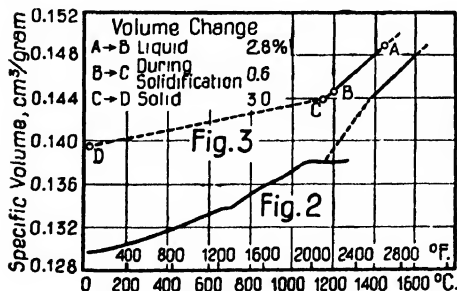


Fig. 2—Specific volume-temperature relation of a white cast iron (Ash and Saeger, Trans., A.F.A., 1932, p. 189).

Fig. 3—Volume changes occurring in a typical gray cast iron (Ash and Saeger, Trans., A.F.A., 1932, p. 194).

For the temperature range from 1070°C. (1958°F.) to room temperature, the coefficient of expansion varies from 0.0000092-0.0000169 per °C. At room temperature the commonly used figure of 0.000010 per °C. is sufficiently accurate for ordinary temperature changes.

Density—The density (g. per cc.) of gray irons at room temperature varies from about 6.95 for open grained high carbon gray irons to 7.35 for close grained low carbon irons. Moldenke gives 7.69 as the density of a white iron. The density of liquid cast irons just above the final solidification temperature is about 6.23. The values for density may be converted into the weight in lb. per cu. ft. by multiplying by the factor 62.428. A gray iron with density of 7.20 weighs about 450 lb. per cu.ft.

Fluidity—The fluidity or "running qualities" of cast iron can hardly be considered a physical constant, but it is so important from a foundry viewpoint that it is considered here. Generally speaking, the running qualities depend on (1) the degree of superheat and (2) the composition of the metal. Carbon and silicon promote the running qualities of the metal. Contrary to general belief Spencer and

*Strictly speaking, the properties listed herewith are not "constants," but may vary considerably according to the composition and treatment of the irons. It is emphasized that the term cast iron denotes a whole series of alloys.

Walding¹ found that higher phosphorus content did not increase the running qualities aside from its influence on lowering the freezing point. Saeger and Ash² found that various metals "run" better in dry sand molds than in green sand molds.

Thermal Conductivity—The thermal conductivity is approximately 0.11 cal. per sq. cm. per °C.

Electrical and Magnetic Properties—Where high permeability, permanent magnetism, or nonmagnetic properties are desired, the unique properties of cast iron may be used to good advantage. Various irons are needed depending on specific services required.

A thorough study of the electrical properties of cast iron has been made by H. J. Partridge (Carnegie Scholarship Memoirs, 1928). He states that the highest magnetic induction and permeability are obtained with cast iron which has been annealed.

Tensile Properties—The tensile strength of gray cast iron made under good foundry practice may range from about 20,000 psi. for soft highly machinable classes to over 60,000 psi. for the strongest, as cast. By use of special heat treatments, small sections have been produced with tensile strengths above 100,000 psi.

The tensile test is a reliable one for cast iron if reasonable care is taken to obtain proper alignment of the grips during the test (see also Section IX, "Classification of Gray Cast Irons").

Gray cast irons do not show a true "elastic limit" as do steels. Gray iron stress-strain diagrams are curved practically from inception. Because of this, it is not possible to establish definite moduli of elasticity. The effective modulus of elasticity at 25% of the ultimate strength will range from about 12,000,000 for some of the weaker irons to over 25,000,000 for some of the higher strength irons. It has been shown that cast iron at room temperature can sustain a static load of 80% of its tensile strength without perceptible creep.

When stressed, all gray irons exhibit some plastic deformation or set. It is possible to remove all set at a given load by a few stressings to that load. For a given material, set increases with load increments, but more rapidly than the load increments.

Transverse Tests (See also Section IX)—The transverse test is widely used for foundry control and specifications. In this test, the test bar is supported on knife edges and broken by a load applied midway between supports. The distance between supports is the "span." Deflection at the center is measured. Usually the ultimate load in pounds and the ultimate deflection in inches are reported. Since the load and deflection depend on the span and size of section, as well as the material, the sizes of test bars and span are specified. Sometimes the results are calculated to "Modulus of Rupture" and the following formulas are used:

$$\text{Round Bar} = \frac{2.546 \times LS}{D^3}$$

$$\text{Rectangular Bar} = \frac{3 LS}{2 BH^2}$$

where L is span
S is ultimate or breaking load
B is width of bar
H is height of bar
D is diameter of bar

There is no constant relationship between tensile strength and transverse modulus of rupture. The modulus of rupture is the higher of the two values and usually increases with increase in tensile strength, but not in the same ratio.

Shear Strength—The shear test is of value in "exploring" a casting; that is, taking test pieces from the casting itself. The ratio of shear strength to tensile strength varies, and the ratio is higher for the weaker irons. On a series of tests covering irons of various tensile strength, the ratio of shear to tensile varied from 1.64 for the weakest iron (15,000-20,000 psi. tensile) to 1.01 for the strongest iron (55,000-60,000 psi. tensile).

Compression Strength—Cast iron is much stronger in compression than in tension. On a series of tests covering many types of cast iron the compression strength ranged from 65,000-160,000 psi. The ratio of compression strength to tensile strength varied from about 4.5-1 for the weaker irons to 2.5-1 for the stronger irons.

¹W. H. Spencer and M. M. Walding, Effect of Soaking Time on Initial Temperature and Analysis of Cupola Melted Iron, Trans., A.F.A., 1931, v. 39, p. 913.

²C. M. Saeger and E. J. Ash, Volume Changes of Cast Iron, Trans., A.F.A., 1932, v. 40, p. 171.

Hardness—The Brinell hardness test is a useful one for gray iron castings. The Rockwell test is also used, employing the B scale and the steel ball. In the "as cast" condition commercial (nonalloy) gray iron castings will range from 130-210 Brinell hardness. The alloy cast irons will run higher and heat treated irons may run over 600 Brinell hardness. Ordinary white irons will range from 321-534 Brinell while alloy white irons may run above 600.

Endurance Limit—The endurance limit, or fatigue strength, appears to vary linearly with the tensile strength. Values for the endurance limit of from 0.4-0.6 of the tensile strength are reported. The values for endurance limit are not greatly reduced for temperatures up to 800°F. Above 1250°F. the endurance limit is as high as the tensile strength under prolonged steady load.

Impact Resistance—Accurate information on impact or shock resistance was not available until recently. For comprehensive data on a large number of irons, see "Report on Impact Testing of Cast Iron," A.S.T.M., Preprint, 1933. In general the impact resistance increases with tensile strength, although this is not true in all cases. Cast irons of high phosphorus content are lower in impact resistance than lower phosphorus irons of equivalent tensile strength.

General Comments on Engineering Properties of Gray Iron—Gray iron combines low melting and molding cost with ease of casting into intricate shapes, rigidity, great compressive strength, and ready machinability.

Shrinkage defects often occur when a large section abruptly changes into a smaller section. When designing gray iron castings, uniform section sizes should be adhered to if possible.

A close grained iron, low in total carbon, is the strongest, toughest and best finishing type of material. The structure and strength of gray irons are controlled by composition and cooling rate. The composition can be controlled in making up the charge. The cooling rate depends on section, size, and to a lesser degree upon pouring temperatures. Hence, castings of nonuniform section are inclined toward diversity in physical properties, and in the same section there is often some difference between the outside and the center of the section. Proper composition will tend to minimize this latter variation.

V—Effects of Common Elements

Carbon—Most commercial cast iron castings contain from 2.50-3.50% total carbon. This carbon may exist as free carbon or graphite (Fig. 4), as combined carbon or cementite (as found in free massive cementite) (Fig. 5), and the cementite lamellae of pearlite (Fig. 6), or in solution (as in molten iron and in austenite).

Graphitic carbon is soft and nontenacious, and in gray iron is found as black flakes (Fig. 4).

Cementite (a carbide of iron, Fe_3C) is intensely hard and possesses little ductility. Under certain conditions it may be decomposed into its constituents, iron and carbon.

At ordinary room temperatures iron can hold only a few hundredths of a per cent carbon in solution. This solubility rather suddenly increases to about 0.85% at the A₁ transformation temperature (approximately 1350°F., depending on composition), and there is further solubility increase as the temperature is raised.

The structure of a given cast iron depends in a large degree on the amount, size, and distribution of the various forms of carbon. The amount depends upon the percentage in the charged metal and on the influence of the melting process. The size and distribution of the various forms depends on the temperatures, time and other factors involved in the melting process, the rate that the metal is cooled from the molten condition, and of course, on the composition. These factors are discussed in detail in various later sections.

Silicon—Because of its action on the carbon, silicon is a very important element in gray iron metallurgy. It promotes and assists the decomposition of the combined carbon (in pearlitic and massive cementite) to ferrite and graphite. In absence of silicon nearly all irons have a white (cementitic) fracture. In changing white iron to gray, silicon makes commercial production of gray iron practicable. For strong irons, just sufficient silicon should be used to insure decomposition of all massive cementite, but not enough to effect decomposition of the cementite in the pearlite. An excess decomposition of the pearlite to graphite and ferrite gives a weak, soft metal.

Silicon also reduces the position of the eutectic some 0.30% carbon for each

per cent of silicon. This means that higher silicon pig irons are often lower in carbon than lower silicon irons. It is easier to produce low carbon cupola metal with higher silicon ranges.

Manganese—Manganese in gray iron may assume two forms: Manganese carbide, which is associated with iron carbide in pearlite; and manganese sulphide, which occurs as small slate colored inclusions throughout the metal. In ordinary commercial ranges, manganese has little effect on the mechanical properties of gray iron. About 0.30% of manganese above the amount theoretically required for combination with sulphur (which is 55/32 times the sulphur percentage) is necessary for mitigating the effects of that element. In most American irons sulphur runs from 0.06-0.12%, hence the usual range of manganese of 0.50-0.80% is sufficient.

Sulphur—Sulphur occurs largely as manganese sulphide, and rarely as iron sulphide. Under proper operating conditions, sulphur does not seem to exert harmful effects on gray iron in amounts up to 0.16 or 0.18%, provided there are sufficient amounts of manganese present to prevent chill. In absence of sufficient manganese, sulphur has a marked stabilizing action on the cementite and promotes chill.

Phosphorus—The phosphorus range in most American irons is from 0.10-0.90%. The irons from northern ores usually run low in phosphorus, and the irons from southern ores generally are in the higher percentage range. The phosphorus content of many foreign irons is much higher than that of typical American irons. Practically all of the phosphorus is present in the component known as steadite, and its effects will be discussed in greater detail under that heading.

VI—Structure of Cast Irons

Structure of Gray Iron—Gray iron is essentially an iron, carbon, and silicon alloy. It may contain the following major structural components: Graphite, ferrite, and any of the products of the austenite-pearlite transformation. With high alloy content, austenite may be retained. With rather slow cooling and low alloy content, pearlite is found. The matrix of most commercial gray irons is largely pearlitic. Rapid cooling or the action of alloys or both may result in various transition products, such as sorbite, troostite, or martensite. "Free" or "massive" cementite is not found in gray irons. Steadite is found wherever phosphorus is present. Phosphorus is found in practically all commercial gray irons.

Pearlite and Ferrite—The carbon in gray iron occurs in two forms. The combined carbon forms pearlite as in steel. In gray iron one part of combined carbon by weight gives about 117 parts of pearlite by volume. As in steel, with low combined carbon the matrix is largely ferrite. However, in gray iron this ferrite has in it a large number of flakes of graphite, and a phosphorus-rich component known as steadite. With about 0.60-0.70% combined carbon (in low phosphorus irons), the matrix is nearly all pearlitic. As in steel, with other factors equal, the strength and hardness increase with increase in pearlite. Leaving transition forms out of consideration, the highest test irons are almost all pearlitic. The converse is not necessarily true.

Graphite—The metallic matrix of gray irons is filled with thousands of curved flakes of graphitic carbon. These flakes are soft and weak and are similar in crystalline make-up to natural graphite (plumbago). Graphite flakes give gray iron its typical dark gray fracture and are responsible for its lack of appreciable ductility and the ease with which it can be machined. By breaking up the matrix these flakes lessen the strength of the iron. In fact their influence is so pronounced that it often overshadows all other factors controlling strength. Graphite flakes exert these effects according to their size, distribution, and amount.

The flakes are much lighter than the matrix, hence they occupy more volume. Three per cent graphite by weight will account for somewhere around 12% by volume. This is one reason for the profound effect of graphite on the strength of gray iron.

Large flakes usually indicate grain growth and slow cooling from casting temperature. This condition usually reduces the amount of pearlite, because of the decomposition of pearlite into graphite and ferrite.

Summing up, increasing graphite lowers strength, promotes softness and allows heavier roughing cuts. Highly graphitic castings contract less on cooling from casting.

Steadite—Steadite, a structural component in cast iron containing phosphorus, is identified by certain white dendritic formations distributed throughout the metal. These formations sometimes form a loosely joined network. The distribution of

the formations indicates that they have concentrated in the last portion of the metal to solidify.



Fig. 4—Graphite in gray iron. $\times 100$.
 Fig. 5—White iron. $\times 175$.
 Fig. 6—Pearlite, ferrite, and cementite in cast iron. $\times 1500$.
 Fig. 7—Phosphide eutectic in cast iron. $\times 1000$.
 All photographs reduced $\frac{1}{2}$ in reproduction.
 Photomicrographs by R. M. Allen, Trans., A.P.A., 1931.

Steadite consists of iron phosphide (Fe_3P) dissolved in iron, and of iron phosphide. In irons of low phosphorus content (under 0.50%) some of the phosphorus, in the form of steadite, is in solid solution. In higher percentages much of the steadite consists of a cellular eutectic (Fig. 7), containing 10.2% phosphorus and 89.8% iron. The melting point of this eutectic is about 1800°F .

Free Cementite—White and mottled irons which have considerably over 0.70% combined carbon contain free cementite, which causes the metal to be hard and brittle. Small amounts of free cementite are present in some gray irons.

Effects of Mass and Cooling Rate—It is well known that the more slowly a given gray iron casting cools from the time of pouring, the lower in strength and hardness it is likely to be. This is frequently referred to as effect of mass or effect of section size, whereas in truth it is more accurately termed effect of cooling rate.

The more slowly a given iron is cooled through the graphitization range, the more complete the graphitization will be. Furthermore, on slower cooling there is greater opportunity for grain growth, including grain size and degree of lamination of pearlite and grain or flake size of graphitic carbon. These effects on the structure are reflected in the physical properties (Fig. 8) showing loss of strength with increase of section size.

Changes in strength and structure with variation in section size are much less apparent in irons of comparatively low total carbon content. For example, a 2.75% carbon, 2.25 silicon iron with no alloys, when properly made, can be cast into a 0.5 in. dia. test bar with no trace of chill and into a 3.0 in. dia. bar with pearlitic matrix having good strength and hardness maintained throughout. Quite frequently the intelligent use of alloys also is beneficial in maintenance of uniformity in strength and hardness over a range of section sizes.

General relationships of strength, structure, hardness, and section size are shown in Fig. 9.

VII—Alloy Cast Irons and Typical Analyses of Alloy and Plain Iron Castings

The term "alloy cast iron" is rather a loose term. All cast irons are alloys. The term "alloy cast iron" is used for those cast irons containing such elements as nickel, chromium, and molybdenum, and which are added because of their effects on the physical properties.

Alloy cast irons are frequently used for more severe service than are ordinary cast irons. In the manufacture of alloy steels, particular care is taken in the melting practice. Similarly in cast iron, the alloys should only be added to good irons to make them better, not to attempt to make a poor cast iron into a good one.

Nickel Cast Iron—Nickel is usually added to gray cast iron in amounts from 0.25-5.0% for general engineering applications. It is often added in combination with other alloying elements, such as chromium or molybdenum. Nickel additions influence machinability, texture, hardness, density, heat, and corrosion resisting properties, and resistance to wear. Nickel, like other alloying elements, must be used with care and discretion if economic benefit is to be derived from it. There is no universal formula for nickel cast iron, but each problem requires its own special prescription.

Nickel acts as a graphitizer and does not form a carbide. It is generally without marked effect on the graphite structure or grain of gray iron. In small amounts,

it will reduce chill and soften partially chilled iron by eliminating hard free carbide, thus promoting machinability. Larger amounts (over 5%) harden iron by forming sorbite and even martensite (Fig. 10). Martensitic irons offer unusual properties in wear resistance and find application in such parts as gears, dies, cylinder blocks, and brake drums.

The value of nickel in gray iron is primarily related to its effect on machinability. The use of nickel permits the production of castings which may be either harder, stronger, and of better structure with equal machinability in comparison with plain iron castings. or more readily machinable for the same hardness, strength, and structure.

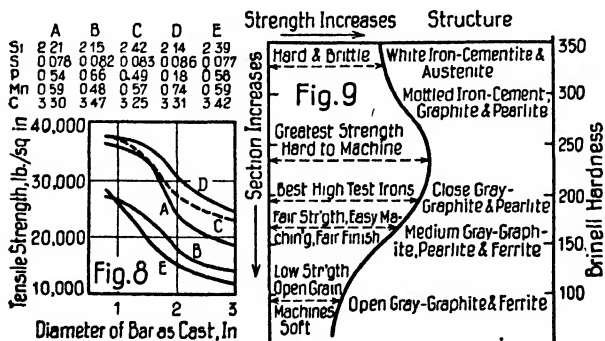


Fig. 9—Qualitative diagram for cast iron showing section, tensile strength, and hardness relations.

production of castings which may be either harder, stronger, and of better structure with equal machinability in comparison with plain iron castings. or more readily machinable for the same hardness, strength, and structure.

Nickel promotes density and freedom from porosity by permitting the use of low silicon without chill or hard spots appearing in light sections. Up to about 4%, nickel in iron of suitable base composition promotes uniformity of grain, hardness, and strength throughout sections of considerable or uneven thickness.

The important relations between silicon content, structure, and machinability are recognized by the foundryman. The machinability may be indicated by the step bar test casting as shown in Fig. 11. The different steps of this test bar are fractured and examined and the hardness and combined carbon determined on the different sections. The effect of decreasing silicon content on chill is also shown in Fig. 11. In Fig. 12 is shown the effect of nickel in reducing chill. As the nickel is increased the hardness and strength of the heavier sections increase slightly, whereas at the same time the lighter sections become progressively more gray and more machinable.

As the amount of nickel is increased to from 10-18% there is a gradual change in structure to nonmagnetic gamma iron (austenitic) with corresponding important changes in properties.

Irons of varying coefficient of expansion can be produced. Up to 5% nickel, the expansivity is slightly lower than that of plain cast iron. At about 20% nickel, the expansion is 50% greater than plain cast iron; between 20 and 36% the expansivity decreases. At 28-29% nickel, the expansion is the same as plain iron. Above 36% the expansivity increases gradually so that at 45-50% the rate again parallels that of plain iron.

Austenitic gray irons (Ni 14%, Cu 5.5, Cr 2-6, Si 2 and total C 3%) are practically free from growth and are nonscaling at temperatures up to 1500°F. They are superior to ordinary gray irons in resisting the action of many acids, alkalis, salts, and other corrosive agents.

The economic application of nickel to the production of specific castings requires a study of the individual problems. In Table I are shown some typical analyses of gray iron castings, including nickel iron castings. These are examples only and no attempt has been made to cover the entire field of alloy and nonalloy cast irons.

Chromium Cast Iron—Chromium is essentially a carbide former in contrast to the graphite forming elements such as silicon and nickel. Chromium in sufficient amount increases the combined carbon and intensifies the chilling propensities of gray iron. Chromium iron double carbides are more stable than straight iron carbides and graphitize less readily.

One of the important uses of chromium is the addition of this alloying element to base irons where additional hardness or wear resistance is required. For example, the base iron in a foundry may have a silicon content of 2.25% and 3.40% total carbon. This iron is suitable for the bulk of the castings produced, but not for some of the heavier castings and for some medium section castings where a maximum of wear resistance is required. Additions of chromium, ranging from 0.40-1.00%, frequently are of considerable value. In heavy sections, the use of chromium helps to give a more uniform structure and tends to eliminate porosity.

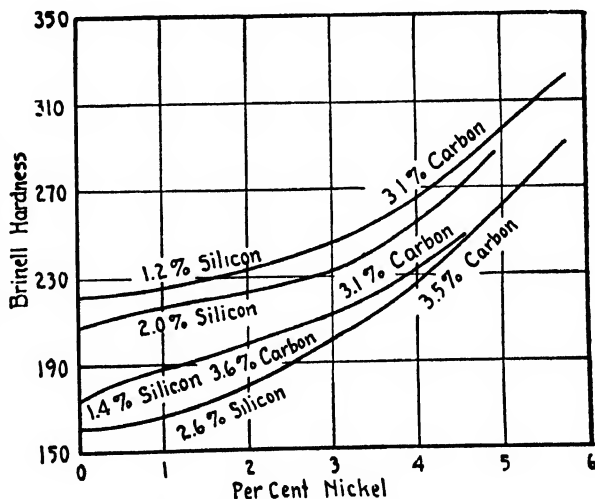


Fig. 10—The effect of nickel on the Brinell hardness of gray iron (arbitration bars).

The approximate effect of chromium on a soft iron is as follows:

Chromium, %	Structure
0	Ferrite and coarse graphite
0.30	Less ferrite and finer graphite and pearlite
0.60	Fine graphite and pearlite
1.0	Fine graphite and pearlite and small carbides
3.0	Graphite disappears
5.0	Much massive cementite
10.0-30.0	Fine cementite

Chromium additions reduce the graphite carbon content, decrease the flake size, and favor the formation of more finely laminated and harder pearlite. For suitable base irons, these effects add to tensile strength, promote finer grain size, and increase hardness. The effects of chromium additions on the Brinell hardness and combined carbon content of gray iron is shown in Fig. 14. Above a certain maximum, usually about 1% chromium in soft irons of medium section, free carbides appear with resulting difficulty in machining. Unless graphitizing alloys such as nickel are added, 3% chromium irons usually have an entirely white fracture. Higher percentages of chromium may be added to produce special purpose white irons, where freedom from scaling toughness or chill are desired. Considerable work is being done on cast irons with chromium contents from 15-35%, and very excellent results have been secured in improving heat and corrosion resistance. For applications up to about 1300°F. (for service comparable to ordinary grate bars) the use of about 1½% chromium has been valuable in eliminating growth.

Chromium increases the tensile strength at elevated temperatures and minimizes tendency to growth in cast iron.

The carbide stability conferred by chromium is useful in gray iron heat treatment because the iron does not offset by excessive graphitization the advantages conferred by structural changes in the matrix.

Nickel-Chromium Cast Iron—Nickel-chromium gray cast irons are currently produced in a variety of compositions, suited to the particular casting or foundry problems for which they were designed. The range is generally not over 3.0% nickel and 1.0% chromium. Nickel and chromium are used together in gray iron primarily for the purpose of refining its structure and of hardening and strengthening it without impairing its machinability.

The addition of about 4.5% nickel and 1.5% chromium to a chilled or white cast iron is being used to give an extremely hard, tough, and strong product. The hardness of such a material will range from 600-750 Brinell as against 380-530 for corresponding grades of plain chilled or white iron. The strength is approximately doubled and the toughness significantly increased.

Nickel and chromium are added to gray iron in the proportion to which they mutually neutralize each other in respect to chill. The resulting alloy iron will have the same chilling tendency as the plain iron to which the alloys were added, and castings made from it will be as readily machinable as

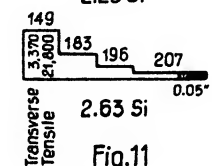
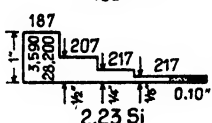
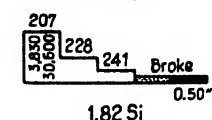
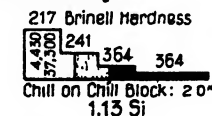


Fig. 11

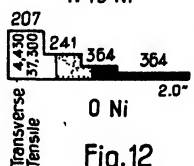
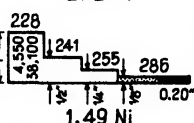
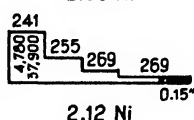
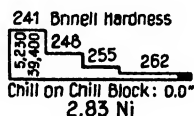


Fig. 12

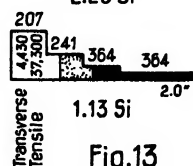
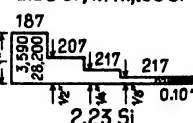
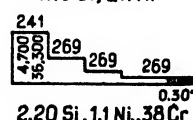
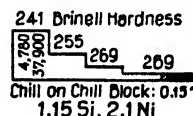


Fig. 13

Fig. 11—Hardening gray iron by decreasing the silicon content. The step bar test.

Fig. 12—Hardening gray iron by adding nickel. The step bar test.

Fig. 13—Hardening gray iron by nickel and chromium in balanced ratio, and comparison of Ni-Cr with Ni cast iron. The step bar test.

castings made from the plain base iron. At the same time the refining, matrix hardening, and strengthening effects of both alloys will be conserved and reflected in

the structure and properties of the casting. Fig. 13 and 15 illustrate the effects of adding nickel and chromium to gray iron.

The usual ratio of nickel to chromium for additions to gray iron is 2½-1. This ratio usually gives good results in respect to machinability and physical properties. Other ratios have been used with good results, the relative amounts of nickel and chromium depending on the base iron and the application.

Nickel-chromium cast irons are used for castings where better structure, greater hardness, wear resistance or strength are required in machinable irons. The use of nickel and chromium is frequently more convenient than adding nickel alone, because it creates less disturbance in the foundry to add nickel and chromium to the regular base iron than to change the cupola mix (in order to lower silicon content) and use nickel alone. Nickel and chromium are frequently cheaper than additions of nickel alone. The usual amounts of nickel and chromium added to gray iron to harden and strengthen it vary within the following limits:

	Nickel, %	Chromium, %
Small addition	0.10-0.50	0.10-0.25
Medium addition	0.75-1.50	0.25-0.50
Maximum addition	2.00-3.00	0.57-1.00

Typical examples of some nickel-chromium cast irons are shown in Table I.

Molybdenum Cast Iron—Molybdenum in cast iron forms both complex carbides and solid ferrite solution. As a carbide former it is much less drastic in its action than chromium. It may have a beneficial effect on the shape of the graphite flakes, causing them to be somewhat nodular in form, with consequent improvement in physical properties.

The addition of molybdenum to a suitable gray cast iron increases tensile strength, transverse strength and deflection, and hardness. Molybdenum is usually added in quantities from 0.25-1.25%. It is the most effective alloying element added to gray cast iron to increase strength. Up to about 1.5% it increases tensile and transverse strengths. Above 2% there is a dropping off in strength (Fig. 16 and 17).

Molybdenum is also used in combination with other alloying elements. For high strength irons, nickel and molybdenum are frequently used in combination. Molybdenum and chromium are also used. Another popular combination is molybdenum, nickel, and chromium.

A number of investigators report that molybdenum increases the wear resistance of cast iron (Fig. 18).

The addition of molybdenum to cast iron promotes structural uniformity in heavy sections. As a result, good density, high Brinell hardness, and high strength are maintained throughout the cross section.

Molybdenum retards the critical transformations in both the liquid and solid state. This makes the volume changes less drastic and the rate of graphitization slower. Such effects help in heat treating processes, also in the retention of strength and other properties at elevated temperatures.

When properly used, suitable machinability is obtained with molybdenum cast iron.

Vanadium Cast Iron—

Vanadium is added to cast iron in amounts varying from about 0.10 to about 0.50%. The following effects are observed:

- (1) Interference with graphitization; that is, stabilization of cementite.
- (2) Smaller graphite flakes and more uniform graphite distribution.
- (3) A tendency to promote sorbitic structure.
- (4) Decreased grain size of matrix.

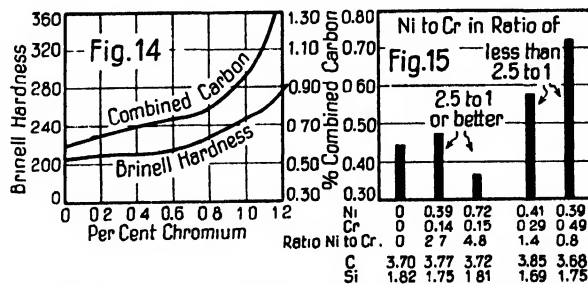


Fig. 14—Effect of chromium on the hardness and combined carbon of gray iron (arbitration bars) (Trantin).

Fig. 15—The Effect of Ni and Cr in different proportions on the combined carbon content of gray iron (Piwowarsky).

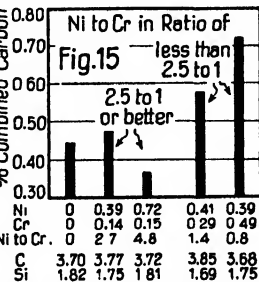


Fig. 15—The Effect of Ni and Cr in different proportions on the combined carbon content of gray iron (Piwowarsky).

(5) Smaller, less pronounced, and less perfectly aligned dendrites in the surface layers of chilled castings. Due to this and (1) above, greater depth, hardness, toughness, and wear resistance of chill result.

(6) Resistance of the carbide to decomposition at elevated temperatures.

These results of vanadium additions are largely a carbide-stabilizing effect. Vanadium is the most powerful of the carbide forming elements. It lowers the eutectoid ratio more rapidly than any other element and gives evidence of forming carbides which are stable at moderately elevated temperature.

Recent work on vanadium cast irons indicate that vanadium additions increase tensile strength, transverse strength, and hardness of gray cast iron. For many commercial applications the vanadium content ranges from 0.10-0.25%. Vanadium is also used in combination with other alloying elements such as nickel, chromium, and molybdenum.

Titanium Cast Iron—Titanium has a graphitizing influence on cast iron similar to silicon but stronger than that element in small amounts. Its addition causes an increase in ferrite formation and a decrease in the chilling tendency. Titanium has a refining action on the size of the graphite particles and this results in increased strength. The deoxidizing and scavenging effects of titanium on cast iron have been reported. Titanium has been used in combination with chromium with favorable results in regard to strength and machinability and good results have been reported from the use of titanium with molybdenum and vanadium.

Table I
Typical Analyses of Some Commercial Gray Iron Castings

Casting	Per Cent							
	Total C	Si	Mn	P	S	Ni	Cr	Mo
Auto cylinder, plain iron.....	3.25	2.25	0.65	0.15	0.10	....	....	....
Auto cylinder, Ni-Cr iron.....	3.25	2.25	0.65	0.15	0.10	0.75	0.30	....
Auto cylinder, Ni-Cr iron, heavy duty.....	3.25	1.90	0.65	0.15	0.10	1.75	0.45	....
Auto cylinder, Ni iron.....	3.25	1.80	0.65	0.15	0.10	1.25	....	....
Auto pistons, plain iron.....	3.35	2.25	0.65	0.15	0.10	....	....	....
Auto pistons, Mo iron.....	3.35	2.25	0.65	0.15	0.10	....	....	0.50
General castings (auto), soft iron.....	3.40	2.60	0.65	0.30	0.10	....	....	....
Piston rings (auto), individually cast.....	3.50	2.90	0.65	0.50	0.06	....	....	....
Brake drums (auto).....	3.30	1.90	0.65	0.15	0.08	1.25	0.50	....
Brake drums (auto).....	2.75	2.25	0.70	0.15	0.08	....	....	0.50
Cams.....	3.10	1.50	0.65	0.15	0.10	2.00	0.60	..
Machinery iron:								
Light service or thin section.....	3.25	2.25	0.50	0.35	0.10	....	....	....
Medium service or heavy section.....	3.25	1.75	0.50	0.35	0.10	....	....	....
Heavy service with heavy section.....	3.25	1.25	0.50	0.35	0.10	....	....	....
Water pipe, sand cast:								
Light and medium.....	3.60	1.75	0.50	0.80	0.08	....	....	....
Heavy.....	3.40	1.40	0.50	0.80	0.08	....	....	....
Chilled plow shares.....	3.60	1.25	0.55	0.40	0.10	....	....	....
High strength iron, plain.....	2.75	2.25	0.80	0.10	0.09	....	....	....
High strength iron, nickel.....	2.75	2.25	0.80	0.10	0.09	1.00	....	....
High strength iron, Mo.....	2.75	2.25	0.80	0.10	0.09	....	....	0.35
Heat resistant iron, fire pots, and kettles.....	3.50	1.15	0.80	0.10	0.07	....	....	....
Caustic pots, Ni-Cr.....	3.30	0.70	0.50	0.10	0.08	1.50	0.60	....
Caustic pots, plain.....	3.60	1.00	0.75	0.20	0.07	....	....	....
Ingot molds.....	3.50	1.00	0.90	0.20	0.07	....	....	....
Car wheels.....	3.35	0.65	0.60	0.35	0.12	....	....	....
Air cylinders, ammonia cylinders, plain iron.....	3.25	1.25	0.65	0.20	0.10	....	....	....
Heavy compressor cylinders, nickel iron.....	3.00	1.10	0.80	0.20	0.10	2.00	....	....
Light compressor cylinders, Ni-Cr.....	3.30	2.10	0.55	0.25	0.10	1.25	0.45	....
Light forming and stamping or forging dies, Ni-Cr iron.....	3.30	1.50	0.60	0.20	0.10	2.00	0.60	....
Heavy forming and stamping or forging dies, Ni-Cr iron.....	3.00	1.25	0.60	0.20	0.10	2.75	0.80	....
Light forging dies, Mo iron.....	3.30	2.00	0.60	0.20	0.10	....	....	1.00
Heavy forging dies, Mo iron.....	3.10	1.50	0.60	0.20	0.08	....	....	1.00
Valves and fittings (medium).....	3.30	2.00	0.50	0.35	0.10	....	....	....

Aluminum Cast Iron—Between 1.0 and 1.75% aluminum is effective in producing extreme hardness in the nitrided case of cast iron. A disadvantage is the fact that when aluminum cast iron is poured, a tenacious oxide skin forms on the surface, getting thicker as the pouring proceeds, and finally creating unsound places in the casting.

Zirconium Cast Iron—In an iron of suitable composition, with low silicon, zir-

contum additions improve physical properties. In amounts from 0.10-0.30% zirconium deoxidizes cast iron and raises strength and resistance to impact.

Copper Cast Iron—During the past few years there has been a large increase in the use of copper in cast iron. The range is from 0.25-2.5% for engineering applications. In a number of commercial applications combinations of copper and chromium have been used, also copper and nickel.

Vanadium cast iron is used for a number of purposes, the following analyses being typical:

Casting	Per Cent							
	Total C	Si	Mn	S	P	V	Cr	Ni
Grate bars	3.68	1.72	0.53	0.09	0.43	0.14	....	....
Locomotive cylinders	3.47	1.54	0.53	0.10	0.49	0.13	....	....
Forming dies	3.40	1.30	0.50	0.08	0.23	0.12	....	....
Steel mill rolls	3.50	1.10	1.20	0.10	0.20	0.35	1.85	4.00
Bottle molds	3.30	1.65	0.60	0.07	0.30	0.14	....	....

VIII—High Strength Cast Irons—The term "High Strength Cast Iron" is usually employed to indicate cast irons ranging above 40,000 psi. in tensile strength. As this term is rather vague, a more desirable method of designating cast iron is to use the A.S.T.M. classifications shown in Section IX (see also definition in Section I).

Rapid progress in the manufacture of high strength irons has been made in the past five years. Irons of 35,000 psi. tensile strength were considered high strength only a few years ago, while today many foundries are regularly producing irons above 50,000 lb. in tensile strength. Strengths in the neighborhood of 70,000 psi. may be obtained in the "as cast" condition.

It should be remembered that the higher strength irons are more difficult to produce and their cost is higher. Also the machinability is usually decreased with increased strength. Consequently these irons should not be specified except where extra cost is justified.

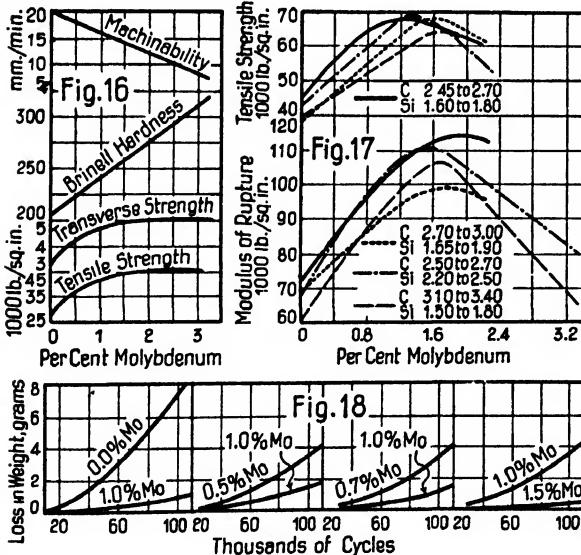


Fig. 16—Effect of molybdenum on the properties of gray cast iron (Smith and Aufderhaar).

Fig. 17—Effect of molybdenum on strength properties of cast irons (Musatti and Calbani).

Fig. 18—Amsler wear tests of cast iron (Musatti and Calbani).

Another cupola iron having about the same strength had almost the identical composition except that 0.35% molybdenum had been substituted for the nickel.

Air furnace irons with minimum tensile strengths of 50,000 psi. may have the

The size, shape, distribution, and quantity of the graphite in cast iron have a large influence on the strength of the iron, usually higher strength irons are low in total carbon content. This is particularly true in irons having tensile strengths above 50,000 psi., the total carbon usually being 3% or under.

In the cupola process a considerable quantity of steel is often used in the charge. Also, alloys may be used for machinability and strength. Therefore, alloying elements such as nickel, nickel-chromium, and molybdenum are frequently used in high strength irons.

Following is the composition of a cupola iron having a tensile strength of about 70,000 psi.: Total C 2.60%, Si 2.15%, S 0.08%, P 0.08%, Mn 0.70%, and Ni 1.10%.

following range of composition: Total C 2.75-3.00%, Si 1.80-2.20%, Mn 0.40-0.60%, S 0.05-0.08%, and P 0.14-0.18%. While this range of composition shows no alloying elements, such as nickel, many air furnace irons have substantial alloy contents.

Electric furnace high strength irons may be made with or without alloys; the following iron had a tensile strength of about 55,000 lb. and a Brinell hardness of 241 on the standard 1.20 in. dia. test bar:

Total C 3.02%, Si 2.35%, S 0.09%, P 0.13%, Mn 0.80%, N 0.44% Cr 0.37%, and Mo 0.58%.

These various examples have been given to show that high strength irons may be made in a number of ways. We are not restricted to any one melting method or one type of composition. However, the high strength irons require closer metallurgical control than do the common grades of cast iron.

High strength gray irons can also be produced by heat treatment of white and gray irons. This is discussed in Section XIV on Heat Treatment.

Meehanite—Meehanite is the trade name applied to cast irons in which the molten metal has been treated with calcium silicide. The metal may be melted in the air furnace, cupola, or electric furnace, and a large portion of scrap metal is usually employed. The composition is adjusted so as to produce a metal which would be a white iron in case the calcium silicide were not added. Calcium silicide is then added and it acts as a graphitizer and also gives a fine graphite structure. Some high strength irons are produced in this manner.

IX—Classification of Gray Cast Irons—There are many classifications which might be set up to cover the alloys of iron, carbon, and silicon known as cast irons. The most important classification of gray irons from an engineering viewpoint is that employed in the A.S.T.M. specification, A48-36.

In these specifications gray iron castings are classed according to minimum tensile strengths of test bars, as follows:

Class, No.	Tensile Strength, Min., psi.
20	20,000
25	25,000
30	30,000
35	35,000
40	40,000
50	50,000
60	60,000

Transverse tests are optional, and the following minimum breaking loads are specified:

Transverse test bar.....	0.875 in., Dia. 12 in. Supports	1.2 in., Dia. 18 in. Supports	2.0 in., Dia. 24 in. Supports
Span length	Breaking Load at Center, Min., lb.	Breaking Load at Center, Min., lb.	Breaking Load at Center, Min., lb.
Class, No.			
20	900	1,800	6,000
25	1,025	2,000	6,800
30	1,150	2,200	7,600
35	1,275	2,400	8,300
40	1,400	2,600	9,100
50	1,675	3,000	10,300
60	1,925	3,400	.....

By agreement between manufacturer and purchaser, deflection values in the transverse test may be specified.

Three sizes of test bars are specified in order to represent various thicknesses of castings by simulating various cooling rates. If the manufacturer and purchaser agree on the controlling section of the casting, the corresponding test bar used is as follows:

Controlling Section of Casting, in.	Test Bar	Nominal Diameter of Test Bar as Cast, in.
0.75	A	0.875
0.75-1.25	B	1.20
1.25-2.00	C	2.00

For sections of castings over 2.00 in., test bar C may be used or a larger test bar may be chosen by agreement between the manufacturer and the purchaser.

The transverse test bars used have the following dimensions:

Test Bar	Dia., in.	Length, in.	Distance Between Supports in Transverse Test, in.
A	0.875	15	12
B	1.20	21	18
C	2.00	27	24

It is recognized that there is no definite factor for correlation between tensile and transverse strengths for various types of cast iron. Tables included in the specification give minimum values only.

It is the intent of these specifications to subordinate chemical composition to physical properties. By agreement between the manufacturer and purchaser, the quantities of any chemical elements in cast iron may be specified.

Other A.S.T.M. Specifications—The A.S.T.M. has developed other specifications for various types of gray iron castings, as follows:

A.S.T.M. Designation	Title of Specification	A.S.T.M. Reference
A44-04	Specification for Cast Iron Pipe and Special Castings	1936 Book of Standards
A45-14	Specification for Cast Iron Locomotive Cylinders	1936 Book of Standards
A46-30T	Tentative Specification for Chilled Tread Cast Wheels	1936 Book of Tent. Standards
A126-30	Specification for Gray Iron Castings for Valves, Flanges and Pipe Fittings	1936 Book of Standards
A142-32T	Tentative Specification for Cast Iron Culvert Pipe	1936 Book of Tent. Standards
A159-35T	Tentative Specification for Automotive Gray Iron Castings	1936 Book of Tent. Standards

Other possible bases for the classification are by composition, by hardness, and by structural features. From an engineering viewpoint there are many definite reasons for the classification employed in the A.S.T.M. Specification A48-36. Other classifications may serve useful purposes, and advances in the technology of cast irons undoubtedly will encourage development of such classifications.

X-Wear—Like the term hardness, the term wear has generic rather than specific significance. In a general way, wear signifies a gradual eating away or dissolution of a structure resulting from the action of mechanically applied agents. Often mechanical wear and deterioration by corrosion act concurrently. The wearing agent may be a fluid (gas or liquid) or a solid. Such agents break off or tear off small particles of the metal, whereas in case of corrosion chemical action results in formation of new compounds, distinct from the original metal.

With a perfect lubricant film there can be no wear. Wear occurs when there is no lubricant, or when the lubricant film breaks down, or when the lubricant is imperfect and a carrier of wearing agents.

In the case of metal to metal wear (no lubricant) gray cast iron reveals a high degree of usefulness. Its highly heterogeneous structure rather effectively inhibits seizure and galling. It not only wears well on itself, but also with many other alloys. It has a tendency to cut much softer alloys, but usually works well with alloys as hard or harder than itself. This property of gray iron is among those responsible for its extensive use in machine tools, where heavy pressures and imperfect lubrication occur, and in automobile cylinders, where temperature and partial lubricant breakdown are factors. An example of metal to metal wear is in automobile break drums. With hardness and lubrication equal, gray iron, with its graphitic structure, is far more free from tendency toward seizure than any of the nongraphitic ferrous alloys.

The properties in gray cast iron which are associated with low rate of wear are pearlitic matrix, high hardness, and high strength. Other things being equal, an iron with a pearlitic matrix will resist wear better than one containing free ferrite.

To compare dissimilar irons, hardness does not always have a direct relationship to wear. However, for the same type of cast iron, higher hardness frequently results in a much lower rate of wear.

Heat treatment or special alloy additions which produce martensite, sorbite, and like hard matrices somewhat improve wear resistance. Usually some increase in resistance to metal to metal wear may be expected from such increased hardness. However, the major gain is from increase resistance to abrasive action (sand or grit). Localized heat treatment (flame hardening) has proved useful.

White cast irons are in general relatively resistant to abrasion. Some of the recent hard white irons not only are resistant to abrasive influences but also have a high degree of resistance to galling and seizure.

Because there are many types of wear it is practically impossible to set up any laboratory test which will give an adequate measure of the wear resistance of a material in service. However, laboratory tests have been of value in helping to develop better materials for resisting wear. Some of the conclusions from laboratory tests are as follows:

- (1) Wear resistance increases with matrix hardness.
- (2) With increasing combined carbon content, the resistance to wear of gray irons increases rapidly up to 0.60% combined carbon and then slightly up to 0.85%.
- (3) Permanent mold cast iron wears away faster than sand cast iron of the same combined carbon content.
- (4) Increasing silicon content decreases resistance to wear.

XI—Machinability—For most gray iron castings machinability is a most important property, yet it is not readily measurable. One shop may consider an iron machinable while the next shop will find it unsatisfactory. Machinability ranges are wide and cast irons may be made to suit many conditions, remembering that ease in machining is usually inversely proportional to the strength of the casting.

Machinability of metals has been variously determined with reference to: (1) Tool life, (2) type of finish obtained, and (3) power required. The difference in machinability with reference to tool life is of the greatest practical importance.

The composition, structure, and physical properties of cast iron extend over a wide range. Dependent upon these factors, cast iron varies from one of the most readily machinable to the most unmachinable of ferrous materials. At one extreme of this range we have completely annealed permanent mold cast iron, which is the most readily machinable; at the other extreme is white or chilled cast iron. Annealed permanent mold cast iron possesses excellent machinability because the structure consists of iron containing no combined carbon, and broken up by a high percentage of finely divided free carbon flakes, together with freedom from burned-in sand at the surface. Chilled or white iron is extremely difficult to machine because its structure is composed chiefly of hard iron carbide in both pearlitic and massive form, unbroken by any flakes of free carbon. The machinability of a cast iron may be said to depend upon the proportions and arrangement of the hard and soft microstructural components. Cast irons may be classified according to their microstructure (and in order of ease of machinability) as follows:

- (1) Ferritic (free carbon and silico-ferrite).
- (2) Pearlitic-ferritic (free carbon, silico-ferrite, and pearlite).
- (3) Pearlitic (free carbon and pearlite).
- (4) Mottled iron (pearlite, free carbon, and enough massive cementite to produce a mottled fracture).
- (5) White iron (pearlite and massive cementite).

Additions of alloys such as nickel, chromium, and molybdenum have an effect on machining. When nickel is used with lower silicon content or with lower silicon and chromium it permits machining irons of considerably higher hardness than could be machined without the use of nickel. The reason for the ability to machine irons of 225-250 Brinell in alloy compositions is that no massive carbides exist in the matrix. As soon as the plain cast iron exceeds a hardness of 200-220 Brinell it usually contains hard carbides, especially at the edges and corners of light castings.

Chromium is a carbide former, and if as much as 0.25% is added to a plain

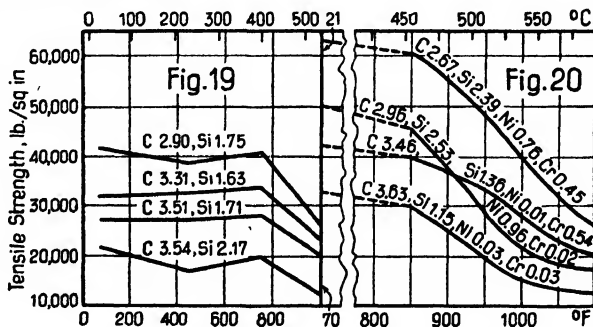


Fig. 19—Tensile strength of various irons at elevated temperatures (J. W. Bolton, Trans., A.F.A., 1930, p. 505).

Fig. 20—Tensile strength after heating 500 hr. Tested at elevated (annealing) temperatures.

cast iron which is already at the limit of machinability, the iron may become unmachinable. Care should therefore be taken in adding chromium, where machinability is a factor. However, on many soft irons, as much as 0.50% chromium may be added with little effect on machinability.

Also the high chromium irons (35% chromium), although white irons structurally, are softer and more readily machinable than ordinary white irons.

Molybdenum is frequently used as an alloy addition in cast iron to obtain increased strength and wear resistance. Where molybdenum is used to increase hardness and strength without the formation of carbides, machinability will usually be inversely proportional to the hardness and strength produced.

The graphitic steels, because the chip is easily broken due to presence of graphite, machine much more readily than ordinary steels of similar combined carbon content and hardness.

The surface condition of iron castings is most important in determining machinability. Frequently castings are condemned as unmachinable when the metal itself is quite machinable, but difficulty is caused by the presence of burned-in sand on the casting. Where burned-in sand is present any attempt to make light surface cuts will cause rapid failure of the tool. A sufficient depth of cut must be made to insure the point of the tool being well below the surface of the casting.

The character of the surface finish obtained in machining cast iron under light cutting conditions is principally dependent upon the size of the graphite flakes and the total amount of the graphite. A high total carbon, high silicon cast iron with large graphite flakes will show a pitted surface when machined due to tearing out of particles of metal in between the graphite flakes. Rough cuts taken on coarse grained cast iron will exaggerate the pitted appearance by tearing out small particles of iron. The lower carbon irons will give a much better appearance on machining.

XII—Effects of Temperature on Cast Iron—The effects of temperature on cast irons may be manifested in two ways: (1) Effects on mechanical properties, and (2) deterioration of the material due to certain structural and chemical changes which may occur at elevated temperatures. These factors are in some cases interrelated.

Boiler codes based upon the A.S.M.E. recommendations do not permit the use of cast iron for pressure containing structures beyond 450°F. and 250 lb. pressure for steam service. This regulation is based upon certain findings by the A.S.M.E. in 1909, and the regulation may be unduly restrictive toward many of our modern cast irons. A proposed code (California—for unfired pressure vessels) permits the use of suitable classes of iron for temperatures up to 650°F.

In other applications requiring considerable mechanical strengths cast irons

frequently are used successfully at temperatures up to about 850°F. Beyond 850°F. practically all ordinary cast irons exhibit enough deterioration to render their utility for severe mechanical duty questionable.

It is possible to discuss the effects of temperature on cast iron only briefly in this section. Those further interested in this subject are referred to the A.S.T.M.-A.S.M.E. Symposium on the Effects of Temperature on Metals, 1931, p. 436-465, and the A.S.T.M.-A.F.A. Symposium

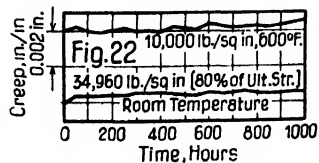
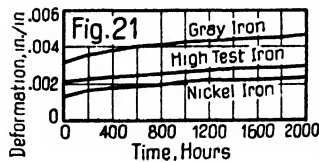
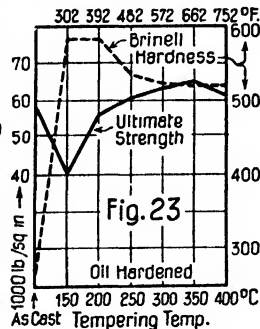


Fig. 21—Time-deformation curves.

Fig. 22—Creep-time curves.

Fig. 23—Effect of quenching and tempering cast iron.



on Cast Iron, 1933, from which much of the material herein has been taken.

When judged by short time tensile tests, cast irons show very slight changes in their original tensility at temperatures up to 800°F. This is shown in Fig. 19 and

20. Kanter gives the following data on some samples of cast iron subjected to exposure for 70 weeks at 600 and 900°F., respectively.

	Original	After 600°F.	After 900°F.
Gray iron	25,300	24,600	18,100
Gray iron	34,400	30,600	23,600

That cast irons have marked resistance to "creep" at 600°F., but that this is somewhat lower at 800°F. is shown by the "creep" curves in Fig. 21 and 22. The curves marked "High Test" and "Nickel" Irons in Fig. 21 were stressed to 10,000 psi. as was the iron stressed at 10,000 psi. at 600°F. shown in Fig. 22. All three irons referred to were in the 40,000 psi. gray iron tensile class. The material marked "Gray Iron" was in the 30,000 psi. tensile class, and was therefore stressed higher in proportion to its tensile strength than the other materials.

Endurance or "fatigue" limit is lowered little up to 800°F., and the Brinell hardness is unchanged. There apparently is an appreciable lowering in compressive strength within this range. The wear resistance of gray irons is one of their unique characteristics, and evidently is maintained at moderately elevated temperatures. The satisfactory wear resistance of gray cast irons is shown by their successful applications in automotive, Diesel, and steam engine cylinders and pistons.

Because of low ductility and comparatively low impact resistance, cast iron should not be employed to resist high dynamic stresses in elevated temperature applications where failure would result in hazards to life or equipment.

Heat Resistant Cast Irons—Heat resistance of cast irons becomes an important factor when these irons are used at temperatures above 800°F. in air, and sometimes at even lower temperatures when used in superheated steam. Heat resistance depends in a large degree on resistance to growth and to certain corrosive influences, chiefly oxidation, which may result in serious scaling.

Growth in cast irons is due both to graphitization and to infiltration of corrosive gases. When ordinary gray iron is repeatedly heated to temperatures above 800°F. (depending on the type of iron) it usually shows a permanent increase in size, or growth as it is called. In most cases in a given iron, the amount of growth is proportional to the maximum temperature reached, and to the number of heatings. In some cases castings have been known to increase 50% in volume. Castings exhibiting growth are weak, misshapen, and brittle.

Irons most resistant to growth are found to have stable carbides and close dense grain structure. Therefore factors which stabilize carbides and produce close grain structure retard growth.

In regular engineering irons, those in the higher tensile classes with lower total carbon usually are more growth resistant and may be satisfactory in this respect up to about 850°F. for long periods. Low silicon usually is desirable and small percentages of chromium frequently prove advantageous. Under some conditions high phosphorus content retards growth somewhat, but due to various drawbacks, high phosphorus irons have not found wide favor for this purpose.

It is obvious that white irons, whose carbon is entirely in the combined form, are more growth resistant than gray irons which contain graphite flakes. Some white irons are limited in application because of their extreme hardness, brittleness, and low strength.

Special irons have been developed which possess extraordinary growth resistance. Perhaps the most widely used of these special irons are the austenitic cast irons containing 14% or more nickel, about 5% copper, and 1-4% chromium. Being austenitic, these irons do not expand and contract in passing through the range 1325-1350°F., where the pearlitic transformation in regular gray irons occurs. They resist oxidation well, even up to 1500°F. These austenitic irons when properly made are more ductile than regular gray irons.

The British have developed a special 6-8% silicon cast iron for which excellent heat resisting properties are claimed. The resistance of this material to deterioration depends on: (1) A completely ferritic matrix (there being therefore no carbide to decompose), (2) raising the transformation temperature above the working range, (3) fine grained graphitic structure, and (4) a dense matrix. The effectiveness of very high silicon content is shown by the following examples showing growth after 10 heatings up to 1832°F.

Carbon, %	Silicon, %	Growth, %
2.1	3.7	0.923
2.5	6.1	-0.011

The high silicon material, known as Silal, must not be confused with so-called high silicon gray irons, which rarely contain over 3.0% silicon. In true gray irons silicon promotes growth, as mentioned previously.

The 6-8% silicon irons are more brittle than gray irons. The 14% silicon irons are growth and scale resistant, but they are brittle.

The advent of the stainless steels has emphasized the high oxidation resistance conferred by high percentages of chromium. The carbide stabilizing tendencies of chromium have been mentioned in an earlier paragraph. It is therefore not surprising that high chromium cast irons (15-35% chromium) have been found both growth and scale resistant. It is claimed that in spite of a white iron structure certain of these alloys can be made machinable, and they have been advocated for applications up to 1800°F.

Certain irons with only modest percentages of chromium (0.30-1.00%) have been found much more growth resistant than gray irons, and possibly somewhat more scale resistant.

XIII—Corrosion of Cast Irons—Gray iron is employed widely in machinery and in equipment of many kinds, and its corrosion resistance is a subject of wide interest.

Use of cast iron water pipe dates back many years. The famous fountains at Versailles were installed about 100 years before the Declaration of Independence and part of the original cast iron piping system is still in use. Today cast iron remains the most widely used material for water main and soil pipe. Under most conditions its corrosion resistance is much greater than that of steel, and its cost lower.

Where stray currents do not cause electrolysis and where soils are not unusually corrosive cast iron pipe usually gives good service for almost indefinite periods. H. O. Forrest⁴ concludes, "It is evident that the rates of corrosion of the usual types of cast iron made in this country do not vary sufficiently to cause any great difference in length of life."

Although gray irons of different grades do not vary much in their degree of corrosion with a given water, different waters vary quite widely in their attack on gray iron. Problems encountered in handling corrosive fluids and solutions are legion. The nature of the fluid, its concentration, temperature and pressure, and the presence of impurities all have an influence on the corrosive action.

Many crude oils and products made therefrom are comparatively noncorrosive and are handled with ease. Some oils of high sulphur content cause more trouble. The choice of gray iron or steel for a given purpose depends a great deal upon the mechanical suitability of the respective metals and on their cost. Many tons of pipe, valves, fittings, and other gray iron equipment are used in the oil industry.

Gray iron castings are used in handling natural gas and in the manufacture and handling of artificial gas. Here again mechanical suitability and cost are the governing factors in choice between iron and steel, since the corrosion problems as a rule are handled equally well by either type of material.

Sulphuric acid has been termed the backbone of the chemical industry. It is manufactured by two processes, the chamber process and the contact process. In either of these processes, where the acid is 60° Baumé or over and is not extremely hot, it may be handled satisfactorily in cast iron. An exception occurs when the acid must be of high purity, and a trace of dissolved iron would be objectionable. However, dilute sulphuric acid attacks gray iron rather rapidly. Since strong sulphuric acid is deliquescent, strong acid in cast iron lines and equipment should be kept away from air. Leakage must be avoided carefully or severe corrosion may result.

The strong dense grades of iron comparatively low in total carbon and silicon usually are the most acid resistant. Special types of cast iron have been devised for acid and other corrosive services. The high silicon irons contain about 14% silicon and are quite resistant to dilute as well as concentrated acids.

While the high silicon irons possess excellent corrosion resistance to many media, their fragility and brittleness are a source of annoyance and trouble. They are difficult to cast and are almost unmachinable. The new austenitic cast irons possess

⁴H. O. Forrest, Corrosion of Cast Iron, Proc., A.S.T.M., 1929, pt. II, v. 29, p. 128.

fairly good resistance to most concentrations of sulphuric acid. These irons usually contain 12-20% nickel, 4-7% copper, and up to about 2% chromium.

Nitric acid production ranks next to sulphuric acid production in acid manufacture. Strong nitric acids and mixtures of nitric and sulphuric acid (mixed acid) attack gray iron slowly. Dilute nitric acid attacks gray iron rapidly. High silicon iron is resistant to both strong and dilute acids. Strong hydrochloric acid is not handled successfully in gray iron or the alloyed irons.

Gray iron is used widely and successfully in the handling of caustics and alkaline solutions. Even strong boiling caustic solutions attack gray iron only slightly. Gray iron equipment finds many applications in alkali manufacturing establishments, being used for caustic fusion kettles. Iron or steel is used for alkaline liquors according to the physical characteristics required. The high nickel, austenitic cast irons are even more resistant to caustic and alkalies than is ordinary gray iron; in fact, some grades containing about 20% nickel (with or without other alloys) are hardly tarnished by boiling caustic or lye.

Special cast irons used for corrosion resistance have been mentioned. The high nickel, austenitic irons have been found resistant to most sulphuric acid, salt and alkaline solutions. The corrosion resistance of the austenitic irons is superior to that of gray irons in all solutions in which they have been tested. Their range of application is rather wide. Due to this and fairly good casting properties and reasonable machinability, the austenitic irons are growing rapidly in popularity.

The 14-15% silicon irons have very high resistance to many types of acid corrosion, except hydrofluoric acid and strong hydrochloric acid. Their rather high corrosion resistance to many fluids and gases is offset by their fragility and high production costs.

High chromium cast irons (15-35% Cr) have recently been produced and apparently will find a number of applications requiring corrosion resistance.

XIV—Heat Treatment of Cast Iron—Cast iron is directly comparable to steel in its reaction to heat treatment, the only fundamental difference in the composition of the two materials being the presence of free graphite particles in gray cast iron. The heat treatment of cast iron may be broadly divided into 3 general classifications: (1) Annealing, (2) quenching, (3) special heat treatment.

Annealing—(a) *Relieving Internal Stresses*—The heat treatment resulting in the relieving of internal stresses is commonly called aging, normalizing, or mild annealing. This can be accomplished by heating from 800-1000°F., holding at temperature from 30 min. to 5 hr. depending upon section size, and slowly cooling in the furnace. This treatment will cause only slight decrease in hardness, very little decomposition of cementite, and only slight change in the inherent strength properties of the metal.

(b) *Softening for Machinability*—The desire in some cases is to soften the casting in order to facilitate machining. A good deal of the production heat treatment of cast iron is of this class. The temperature range most commonly used is 1400-1500°F., although temperatures as low as 1200-1250° have been used satisfactorily. Highly alloyed irons are sometimes annealed at temperatures as high as 1800°F. In all annealing, care should be taken to prevent oxidation of the casting.

In general, softening for machinability is attended with a decrease in strength and amount of combined carbon and an increase in graphite content. Irons containing carbide forming alloying elements such as chromium are more resistant to annealing than the ordinary gray iron. Temperatures used for annealing of these irons are considerably higher.

Completely annealed ordinary cast iron may have Brinell hardness values from 120-130, whereas completely annealed alloy irons may have Brinell hardness values of 130-180, depending upon the composition.

(c) *Annealing White or Mottled Irons as Cast to Obtain Higher Strength Gray Iron*—In order to obtain commercially machinable irons of from 60,000-90,000 psi. tensile strength, irons white or mottled as cast are annealed to effect the decomposition of carbides into ferrite and graphite. Such irons are sometimes referred to as semimalleable and pearlitic malleable irons. They should not be confused with true malleable iron, which is composed of ferrite and rounded graphite particles called temper carbon. The total carbon in these special irons is usually held at from 2-2.8%. The silicon content depends upon the section, but does not exceed 1.8%. A typical annealing cycle for this material is as follows:

Heat to 1700-1750°F. and hold for 1½-3 hr. Cool to 1375° for 3 hr., then subject

to one of the following: (a) Oil quench and temper, (b) air cool, (c) cool slowly in furnace.

The Brinell hardness of this type of iron will vary from 150-400 according to composition and treatment. Alloying elements such as nickel, chromium, or molybdenum may be used. The resulting product has high strength with measurable ductility and good impact resistance.

(2) *Quenching and Tempering*—In order to increase wear and abrasion resistance of cast iron, quenching from above the critical temperature is employed. Common soft gray irons that have a coarse interlocking structure and a ferrite matrix are not materially improved by heat treatment. They do not harden satisfactorily, while tempering may or may not improve their strength. Heat treatment should be employed to make good cast iron better and not to attempt to make poor cast iron into a fair product. As in steel practice, the addition of alloys such as nickel, chromium, or molybdenum has a marked effect on the response to heat treatment.

To heat treat satisfactorily, graphite flakes should be small and well distributed, while the matrix should preferably be pearlitic or sorbitic. Graphitic carbon of cast iron suitable for heat treatment should approximate from 2-2½% and the combined carbon should range from 0.50-0.80%. Given these conditions, gray iron castings respond to quenching and tempering much in the same way as carbon tool steels. The hardness increases in direct relation to the rapidity of quenching from above the critical temperature. Softening after hardening proceeds uniformly as the tempering temperature rises above 350°F. Tempering below 350°F. has little effect on hardness or structure. The strength and impact resistance are definitely improved by tempering.

The hardening effect brought about by rapid cooling from temperatures above the critical point is usually accompanied by a deterioration in strength. This deterioration is immediately restored by tempering (Fig. 23). Thus by suitable hardening and tempering a definite improvement in strength properties can be obtained.

The casting should be heated for hardening very carefully. It should be heated slowly and uniformly to the quenching temperature, then held for a sufficient length of time to insure that all parts have received the maximum heat. A safe minimum is 30 min. for comparatively small castings. To promote economy of operation, if the castings are small and of symmetrical design, they may be preheated at from 300-500°F. in one furnace and then transferred to another furnace, held at the quenching temperature, with little danger of cracking. The quenching temperatures used on most irons in production at the present time are from 1450-1550°F. The quenching medium most commonly used is oil, although water is also used to a limited extent. Some castings may be quenched in air.

The composition of the material is largely governed by the requirements of machinability in the as cast condition and the response to heat treatment. The casting to be hardened usually is rough machined before hardening and tempering and is finished by grinding. Small amounts of growth occur on quenching and allowance must be made for this in leaving stock for finish grinding. Where strength and shock resistance are not of particular importance, the tempering operation may be omitted.

Cylinder liners for use in heavy duty internal combustion engines have been heat treated both in this country and in England to secure a marked increase in hardness and wear resistance. The Brinell hardness has been increased from about 225 to over 400. The wear resistance has increased in line with the increase in hardness.

In suitable thin sections, ordinary unalloyed cast iron is capable of being hardened by oil quenching from suitable temperatures. In thicker sections, it has been shown that an ordinary cast iron is not very susceptible to hardening by quenching in oil. The presence of alloying constituents such as nickel, chromium, or molybdenum increases the susceptibility to hardening. The alloying elements in cast iron, just as in steel, have the effect of increasing the depth of penetration of hardness and also increasing the degree of hardness obtainable.

An excessively high hardening temperature is accompanied by definitely inferior results both as to hardness and strength values. The lower quenching temperatures tend to produce the best results.

The metal may be annealed before hardening without appreciably affecting the response to quenching or hardening properties, provided coarse interlocking graphite is not present. Care should be exercised in respect to sudden changes in tempera-

ture both in heating and quenching, particularly where castings are irregular in section and where size is large. It should be remembered that cast iron is more fragile than steel.

Some alloy cast iron compositions can be hardened by removing red-hot castings from the molds and cooling the castings in air, or by reheating to above the critical temperature and air cooling. Such cast irons have a matrix that may be sorbitic or martensitic. Nickel-chromium and nickel-molybdenum irons have been used. The use of a low carbon iron (2.50-2.80 total carbon) with a manganese content of about 2% results in materially reducing the A₁ point so that the castings can be hardened by quenching in still air or in an air blast. Good results have also been reported on cast irons with manganese 1% and nickel 1-2%.

(3) *Special Heat Treatment*—(a) *Nitriding*—The nitriding process for cast iron has been in use for several years and considerable experimental work has been done. Parts requiring extremely high wear resisting properties may be economically nitrided. The nitriding process consists in subjecting the casting to temperatures of from 950-1100°F. in contact with anhydrous ammonia gas for a period of time ranging from 20-90 hr. Low total carbon, chromium-aluminum irons for nitriding purposes were originally developed somewhat similar to the steel used for nitriding. A number of other compositions have also been developed for nitriding. A typical cast iron used for nitriding is as follows:

Total C 2.61%, Si 2.58%, Mn 0.61%, S 0.07%, P 0.10%, Cr 1.69%, and Al 1.43%.

Nitrogen hardened cast iron has been used in the production of cylinder liners for various types of engines, compressors, and pumps. It is claimed that excellent wearing results have been obtained.

(b) *Flame Hardening*—Flame hardening is being used to a considerable extent on gray iron castings, particularly where a hardened surface is desired for wear resistance. A large proportion of automobile camshafts are made of cast iron and most of these are hardened on the cams by means of the acetylene flame.

XV—Welding of Cast Iron—For information on the welding of cast iron see page 220.

Malleable Iron

By H. A. Schwartz*

Description of Malleable Iron—The production of malleable cast iron consists of two distinct steps. The first is the production of white iron castings which are brittle and hard. The second step is the annealing or graphitizing of the white iron so as to secure a ductile product known as "malleable cast iron." The annealing or graphitizing changes the combined carbon to free carbon in the form of temper carbon.

The free carbon of malleable cast iron is chemically and crystallographically identical with that in gray cast iron, but differs greatly in form. The graphite of gray iron, formed near the freezing point, has the shape of fish scales. That of malleable cast iron, formed at lower temperature, is crumpled up into nodules.

Malleable cast iron consists almost entirely of ferrite and carbon. Gray cast iron contains usually much pearlite and sometimes either ferrite or cementite.

Melting Furnaces—For the production of high grade malleable iron castings, that is, for castings with high tensile strength and elongation, the reverberatory type of furnace is used for melting. In this country the air furnace is used. This is often coal fired, either by hand or more often mechanically by means of pulverized coal. There are also some oil fired installations. The electric furnace is now being used either alone or in duplexing or triplexing.

Sectional views of a typical air furnace are shown in Fig. 1. The furnace walls are of firebrick, supported and inclosed by cast iron side and end plates. The hearth A is built of silica sand. Coal is burned in the firebox B; the air is forced through the fire by a blower discharging into the ash pit C; the ash pit doors D are kept closed. Air is also admitted through the tuyeres E, to aid in the combustion of the gas and in forcing the flame over the front or firebridge wall F. The roof of the furnace consists of a series of removable firebrick arches or bungs supported in cast iron frames. A sufficient number of these are removed to permit the introduction of the melting stock.

If pulverized coal or oil is to be used the firebox is replaced by a combustion chamber into which the burner points through an opening in the head wall near the roof.

Recently furnaces have been developed, working on the general principle of an air furnace, in which the entire hearth and roof are modified into a cylindrical structure rotating about a horizontal axis. In such furnaces that part of the cylindrical hearth which is above the level of the metal becomes highly heated. As the hearth rotates this hot refractory is carried below the surface of the metal imparting its heat thereto. The net effect is hotter iron for a given roof temperature. These furnaces are commonly used with recuperators furnishing air for combustion at about 450°F. Recuperators have also been found economical on air furnaces of the stationary type.

The air furnace is used for high grade malleable cast iron because it is possible to secure a more uniform composition of metal than with the cupola furnace.

In Europe, particularly in Germany, the open hearth furnace is used for the production of high grade malleable iron. One reason for using the open hearth furnace is that fuel is not available for the air furnace.

Air Furnace Charge—The charge used in the furnace consists of sprue, pig iron, malleable scrap, and steel scrap. The sprue is charged first, the steel and malleable scrap are charged on top of the sprue, while the pig iron is charged last.

Duplex and Triplex Processes—Considerable white iron for use in making malleable iron is produced by the duplex and triplex processes. In the duplex process, the iron is melted in the cupola, using a large percentage of steel in the mix so as to obtain a low carbon content, and is then introduced into the electric furnace. Steel additions may be made in the electric furnace where a final adjustment of composition is made and the desired temperature attained. In the triplex process, the charge is melted in the cupola and a portion of the resulting metal is treated in the Bessemer converter to reduce carbon. The final step consists of mixing in the electric furnace the necessary amounts of cupola metal, liquid steel, and alloys to give the desired composition. Duplexing with the use of cupolas and air furnaces

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has been practiced both in the U. S. and abroad. There is also a limited use of cold melting in electric furnaces.

Cupola Furnace—The cupola furnace is used for malleable iron castings of lower tensile properties than are secured by melting in the reverberatory furnaces. Malleable pipe fittings come under this classification. Decreased tensile strength is not necessarily a detriment for such purposes. It is claimed that such iron as is made in the cupola produces fittings freer from leakage, at as high pressure, than lower carbon fittings. Advantages in machinability and freedom from galvanizing difficulties are also considered to exist. The latter advantage is probably due to a rather low phosphorus content.

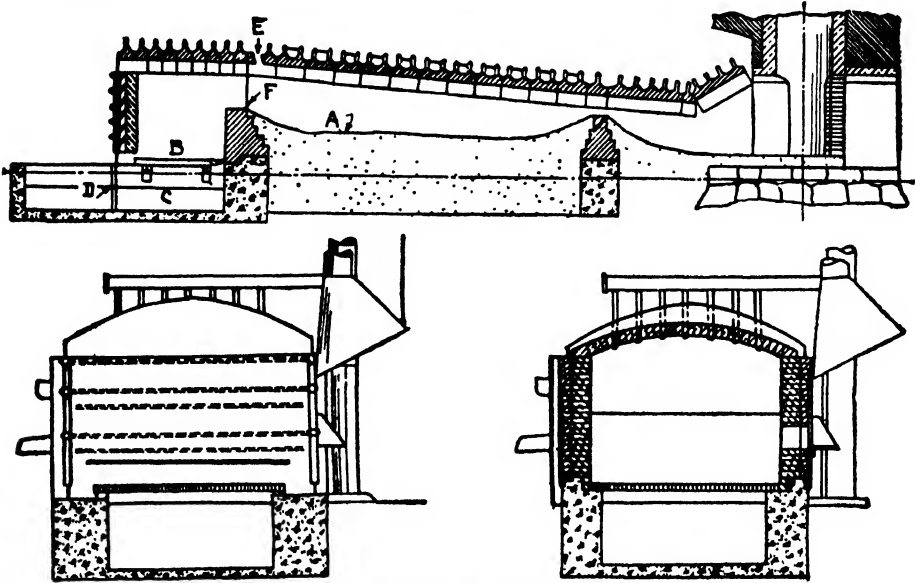


Fig. 1—Sectional Views of an Air Furnace.

Composition of Malleable Iron—The composition of the white iron produced by any of these processes is adapted to the desired purpose. Any physical property of malleable is that of the metal body through which the carbon is scattered modified by the presence of that carbon which in effect acts like so many holes. The properties of malleable cast iron are therefore largely controlled by the amount of carbon present.

For various purposes the carbon may be as low as 2.00-2.10 or as high as 2.90-3.00% (or even more). In general high carbon makes the metal weak and less ductile, but makes the castings sound and of better surface. Many believe that increased carbon is favorable to increased machinability.

In high carbon iron the silicon is kept low, and in low carbon iron it is kept high in order to secure the most desirable properties. Silicon may be as much as 1.20-1.30% in small, low carbon castings or as low as 0.50 or 0.60% in large, high carbon castings.

In special cases, particularly when cross sections of castings are not too thick, the practice of dropping the carbon well down toward 2% and raising the silicon to as much as 1.6% has been advocated and to some extent practiced. Such irons can be made in air furnaces but are particularly adapted to melting in electric furnaces, often of the rocking indirect arc type or in the rotary air furnace. In electric melting particularly the charge is frequently largely steel scrap, petroleum coke and ferroalloys. If the carbon is dropped so far that in the presence of the existing silicon the iron is no longer eutectiferous the resulting products can no longer be classified as cast irons. They have certain analogies to malleable iron but also certain essential differences and should probably be called steel.

The manganese and sulphur go up and down together; manganese around 0.25% and sulphur around 0.05% may be encountered or manganese around 0.40% and

sulphur around 0.14%. Phosphorus is almost always below 0.20% and may go down to 0.100% or less.

Annealing Malleable Cast Iron—The purpose of annealing is the destruction of all combined carbon in the casting by converting it into graphite. The free, massive cementite can best be completely broken up above the critical point (A₁). The excess carbide which exists when cooled as pearlite must be decomposed below A₁.

The castings are annealed by packing in iron pots, sometimes using a packing material such as sand, cinders, or mill scale to support the castings. The pots are then placed in furnaces and heated in accordance with a predetermined cycle. As a general rule, the annealing furnace is brought up to temperature as rapidly as possible.

A typical annealing cycle for a stationary batch type furnace is as follows:

Time heating to 1500°F.	45 hr.
Time holding above 1500°F. (max. 1650°F.)	50 hr.
Time cooling	60 hr.

In some foundries and for some castings it has been found possible to do away with packing material in the annealing process.

Continuous car type furnaces are frequently used for the annealing of malleable iron castings. The castings are loaded in pots on cars and the cars move slowly through the furnace. The various zones of the furnace are maintained at the required temperatures. Car bottom type batch furnaces are also in use which conserve time by conserving the heat content of the furnace structure. In these furnaces the car is first inserted in a furnace at maximum temperature and then removed to a second furnace which is at the proper temperature for completing the reaction. Considerable savings of time are made by accelerating the heating and cooling rates and by making it possible to remove a charge at a temperature at which it could not be handled in a stationary bottom furnace.

Where small lots of castings are heat treated in accurately controllable furnaces, and especially when high silicon metal is used, great modifications are possible in the direction of a shortened anneal.

Using the most modern furnace designs, dispensing with pots and with the most careful control in the manufacture of the hard iron an annealing time of around 50 hr. total time can be commercially maintained. In smaller units in which temperature gradients may be less this could be reduced somewhat further. Highly reputable persons report operating times around 30-36 hr. A time around 70 hr. is readily attained even in large continuous units in which the temperature gradient in pots is an important consideration. The saving of time in all these cases is made by cutting out time wasted in needlessly slow heating and cooling, cooling to too low a temperature or waiting for cold parts of a charge to come to temperature.

It is always important to remember that the complete elimination of pearlite is the most time consuming factor of an annealing cycle. If even small amounts of pearlite are tolerable or perhaps desired, a disproportionately large time saving may be possible. Those who speak of reducing annealing cycles do not always clearly differentiate between making malleable castings and making pearlitic malleable castings.

Some very short cycles, 15 to 18 hr., have been reported. In considering such a process it is always necessary to take account of the size of charge which can be handled and maintain uniformity of result, whether the required chemical composition is safe from the viewpoint of occasional or frequent occurrence of very poor iron and whether the product is actually as free from pearlite as is required for good machining. Castings have in fact been quite satisfactorily annealed in as little as 3 hr. by methods not to be recommended for tonnage production.

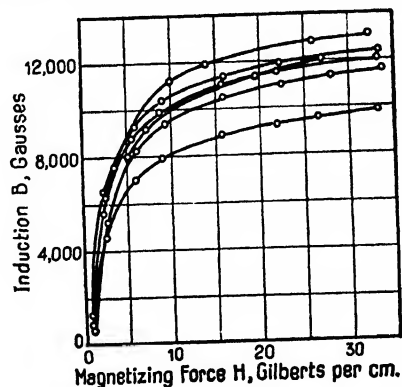


Fig. 2—Magnetization Curves for Various Malleable Irons.¹

¹Reproduced from the "Symposium on Malleable Iron Castings," published by the A.F.A. and I.S.T.M.

Any maximum temperature up to about 1800°F., where the castings become too soft to hold their shape, may be used. With increase in temperature comes a great decrease in the time to break up the cementite of white cast iron. The slow cooling or holding under 1400°F., necessary to break up pearlite, can not be so much accelerated but under favorable conditions a total annealing cycle of 30-48 hr. has been used. This is often done with special forms of electrically heated furnaces in which the castings and heating units are sealed up together in an air tight chamber. The use of tubes of scale resisting alloys, heated internally by gas flames and possibly also by oil or powdered coal flames, has also found favor as a means of heating a charge in a completely sealed chamber. The result is equivalent in principle to annealing electrically. Large lots of castings can not be heated fast and uniformly enough to secure the fastest annealing time. Especially for the low carbon, very high silicon type of metal continuous annealing furnaces operating without packing have been advocated by some in order to produce an extremely short annealing cycle. Although a reduction in annealing time is highly desirable it must be remembered that the more elaborate equipment required sometimes outweighs in money value the increased production and that most of the quick annealing products and processes are more closely limited in application and operation than the slower processes.

Metallurgical Principles—Malleable cast iron of acceptable quality is intended to consist entirely of ferrite and "temper" carbon which is graphite in round nodules instead of in flakes as in gray iron. This result requires that the original casting must be entirely free from flaky graphite such as is produced during freezing. To accomplish this the composition of the melt must be kept within certain limits, mainly as to carbon and silicon. The cross section of the casting also plays a part because it determines the cooling rate in the mold which has an effect on the amount of graphite separating. Heavy sections must be lower in carbon and silicon than light sections.

During annealing iron carbide "cementite" dissolves at the surface of contact of cementite and austenite; the carbon migrates in some form the surface of graphite nodules and there crystallizes out. Somewhere in the process, cementite is dissociated into iron and carbon.

Under most operating conditions the rate of migration determines the annealing rate. If that is so, annealing should be accelerated by any process which increases the number of spots of graphite in a unit volume, for this reduces the distance which the carbon has to travel. This number can be altered to a considerable degree by changes in melting and heat treating methods. Some elements accelerate annealing, particularly Si, Al, Ti, Zr and U and to a less extent Cu, Ni, P and probably Co. Others retard annealing, particularly Cr, Mn, V and to some extent Mo among the metals, and S, Se and Te among the nonmetals. Sn, Ce and La are also regarded as possible retarders. No one yet knows the mechanism by which these elements act. Like all chemical reactions graphitization goes on faster the higher the temperature. The process can not be completed above the critical point, for considerable carbon dissolves immediately above that temperature and can not be separated in the free state except by very slow cooling or long holding. Of course the completion or "second stage" of annealing below the critical point cannot be hurried by raising the temperature for which the A_1 point is a ceiling.

Unfortunately many of the factors which will hurry annealing are not favorable to the safe maintenance of high quality. They therefore frequently involve additional care and expense if an acceptable product is to be turned out.

Use—Malleable cast iron is used for castings which must withstand shock and where gray iron would probably fail because of low ductility. A condensed list of malleable iron castings is given in Table II.

Alloyed Malleable Iron—Malleable iron is understood to be an entirely ferritic material. Maintaining that limitation, only copper and somewhat problematically molybdenum* have so far come into any prominence. Copper somewhat facilitates annealing and improves the strength and to some extent, the ductility of malleable when present in an optimum amount of about 1%. Such alloys are capable of precipitation hardening with considerable increase in strength, and indentation hardness and little effect on ductility. It is reported that copper benefits high carbon malleable more than low carbon in the annealed condition.

*See the article in this Handbook, Pearlitic Malleable Iron. The information on copper is from Lorig and Smith, Trans., A.F.A., 1934.

Table I
Composition and Properties of Malleable Iron*

	For Classes of Iron to Meet			
	A.S.T.M. Specification A47-33, Grade 35018	Most Probable Value	A.S.T.M. Specification A47-33, Grade 32510	Most Probable Value
	Range		Range	
Chemical Composition¹—White Iron				
Carbon, %	1.75-2.30	.....	2.25-2.70	.....
Silicon, %	0.85-1.20	.....	0.80-1.10	.....
Manganese, %	less than 0.40	.....	less than 0.40	.....
Phosphorus, %	less than 0.20	.....	less than 0.20	.....
Sulphur, %	less than 0.12	.....	0.07-0.15	.....
Chemical Composition—Finished Product				
Temper carbon, %	less than 1.80	.....	less than 2.20	.....
Silicon, %	less than 1.20	.....	less than 1.10	.....
Manganese, %	less than 0.40	.....	less than 0.40	.....
Phosphorus, %	less than 0.20	.....	less than 0.20	.....
Sulphur, %	less than 0.12	.....	less than 0.13	.....
Physical Properties				
Specific gravity	7.20-7.45	.....	7.34-7.25	.....
Shrinkage allowance, in. per ft. ....	.....	†	.....	†
Coefficient of thermal ex- pansion, per °C. ....	.....	0.000012	.....	0.000012
per °F. ....	.....	0.000066	.....	0.000066
Specific heat, cal. per g. per °C. average be- tween 20 and 100°C. ....	.....	0.122	.....	0.122
Mechanical Properties				
Tensile strength, psi.	53,000-60,000	57,000	50,000-52,000	50,000
Yield point, psi.	35,000-40,000	37,500	32,500-35,000	32,500
Elongation in 2 in., % ...	18-25	22	10-18	14
Modulus of elasticity in tension, psi. ....	.....	25,000,000	.....	25,000,000
Poissons ratio .....	.....	0.17	.....	0.17
Ultimate shearing strength, psi. ....	.....	48,000	.....	48,000
Yield point in shear, psi. ....	.....	23,000	.....	23,000
Modulus of elasticity, psi. ....	.....	12,500,000	.....	12,500,000
Modulus of rupture in torsion, psi. ....	.....	58,000	.....	58,000
Brinell hardness number .....	.....	110-145	110-135	.....
Charpy impact value, ft.- lb., "key hole" notch 0.04 in. radius at bot- tom, 0.394 in. square bar .....	.....	.....	.....	7
V-notch—0.197 in. depth of notch .....	.....	.....	10-14	12
Izod impact value, ft.-lb. (using V-notch 0.394 in. square bar, 0.079 in. depth of notch) .....	.....	16	10-14	12
Fatigue endurance limit, ² psi.	22,000-30,500	27,000	25,000-28,500	25,500
Endurance ratio (endur- ance limit ultimate strength) ²	0.43-0.54	0.50	.....	0.50
Resistivity, microhms per cc. ....	.....	30	.....	32

*Reprinted from Cast Metals Handbook, published by the American Foundrymen's Association.

¹These chemical compositions are not to be taken as specifications, because the specifications for mechanical properties can be met by a number of compositions, depending on foundry practice and conditions.

²The longer range of values for grade 35018 material is in part due to more frequent investigations.

The tensile strength of iron containing about 2.35% total carbon was not materially altered by any amount of copper up to 2.68% although the yield point was raised 6000 psi. The elongation was raised from 14.5-22.2% by 0.63% copper and then fell off to about 16%. In iron containing about 2.70% carbon the tensile strength was raised progressively with increases of copper by 14,000 psi. for 2% copper, the yield point was raised 16,000 psi. and the elongation was not uniformly affected. Precipitation hardening may raise the tensile strength by from 2000-10,000 psi. depending upon other conditions, the yield point by somewhat greater amounts with little and variable effect on elongation. The endurance ratio is not materially altered by copper so that the increased tensile strength involves corresponding increments in fatigue resistance. As annealed the Charpy value is increased by the presence of copper.

The information as to the effect of molybdenum on ferritic malleable is as yet not sufficiently conclusive to permit of a survey. The concentrations of molybdenum which could be used within this limitation are, of course, limited. The use of an increased silicon content in the presence of molybdenum seems to have some merit.

A strengthening effect on malleable due to small amounts of aluminum has been reported. The method has apparently not been introduced into practice and is generally regarded as dangerous due to the possible formation of "primary" graphite during freezing.

Table II

**Classification of Industries, with Condensed List of Products, in Which
Malleable Castings Are Used¹**

Agricultural Implements

Plows, tractors, harrows, reapers, mowers, binders, cultivators, rakes, spreaders, dairy and poultry equipment, presses, tools, pumps, wagons, fence parts.

Automobiles

Parts for frame, wheels, springs, brakes, motor transmission, axles, steering gear, body, accessories.

Boilers, Tanks, and Engines

Boilers, tanks, fittings, engine parts, out-board motors, Diesel engines.

Building Equipment

Hardware for windows, doors, garage equipment, awning hardware.

Conveyor and Elevator Equipment.

Chains, buckets, pulleys, rollers, cranes, hoist, fittings.

Electrical and Industrial Power Equipment

Motor and generator parts, pumps, stokers, electric locomotives and tractors, steam specialties, outlet and switch boxes.

Hardware and Small Tools

Pneumatic and portable tools, miscellaneous tools, saddlery, hardware, table and kitchen utensils.

Household Appliances

Stoves, sewing machines, refrigerators, washing and ironing machines, vacuum cleaners, dishwashing machines, oil burners, electric fans and toasters, radios.

According to the Department of Commerce, there are about 150 plants in the industry, with an estimated annual capacity of 1,350,000 tons.

¹Reprinted from the "Symposium on Malleable Iron Castings," published by the A.F.A. and A.S.T.M.

Machine Tools

Lathes, planers, shapers, grinders, screw machines, gear cutters, drills.

Machinery for Special Uses

Textile, cement, rubber, shoe, mining and quarrying, grinding, forging, foundry, bakery, woodworking, bottling, ice, laundry industries.

Marine Equipment

Anchors, chains, capstans, fastenings, towing bits, hardware.

Metal Furniture and Fixtures

Stoves, beds, desks, filing cabinets, shelving, hotel supply equipment.

Municipal, State and Public Service

Manhole covers, posts, guard rail equipment, highway markers, transmission and telephone line fittings, electric railway fittings.

Pipe Fittings and Plumbing Supplies

Elbows, unions, reducers, flanges, valves, bolts, nuts.

Railroads

Wide variety of parts for construction of locomotives, freight and passenger cars; guard rails, miscellaneous.

Road and Contractor's Machinery

Rollers, excavators, cranes, hoists, tractors, graders, scarifiers, mixers, pavers.

Toys and Specialties

Sleds, wagons, automobiles, bicycles, carriages, gun parts.

Pearlitic Malleable Iron

By H. A. Schwartz*

Malleable iron was originally valued mainly because of its ductility and machinability. Of late, uses have suggested themselves which require increments in strength, yield point, or fatigue resistance even at a sacrifice of elongation or ease of cutting. Various processes have been suggested for making what is probably best called, generically, "pearlitic malleable," even though the "combined" or "agraphitic" carbon is sometimes present as sorbite or even martensite.

"Pearlitic malleable" is now intended to be understood as designating white cast iron subsequently graphitized by heat treatment so as to intentionally leave significant amounts of carbon in the "combined" or "agraphitic" form.

These metals can be subdivided into groups according as to whether:

- (a) They are produced by stopping the graphitizing operation before all the agraphitic carbon is converted into graphite or by completely graphitizing and then recombining some carbon.
- (b) When produced by incomplete graphitization the retention of agraphitic carbon is brought about mainly by the shortening of the cycle or by the presence of alloying elements.
- (c) Their metallography has certain particular characteristics as to kind and distribution of given constituents.

The methods of melting, molding, and casting are in any event exactly the same for pearlitic irons as for ordinary malleable except for the introduction of alloys if these are to be used. It is doubtful whether in the customary amounts alloying elements have any effects of themselves on the properties of pearlitic malleable. They are used primarily to facilitate the control of combined carbon which would be possible but sometimes more difficult without them. Some processes carried out to give a matrix of particular character, such as spheroidizing, go on so slowly that in unalloyed malleable the destruction of agraphitic carbon by graphitization would outrun its conversion into the desired form and a retarder of the graphitizing reaction is advantageous.

The usual retarding elements are manganese in an amount up to 1% more than the concentration otherwise suitable for normal malleable, chromium often in low concentration of 0.10-0.25% but occasionally suggested higher, and molybdenum seldom up to 1% and frequently about ¼% or even less. Some see virtue in the combined use of rather large amounts of retarders and additional accelerators, as for example, silicon with chromium or molybdenum.

All the interrupted annealing processes begin with an equivalent of the first stage of annealing of malleable cast iron. The alloy is graphitized as far as it will go at a temperature somewhat above the critical. From there on the process depends upon whether laminated pearlite or a spheroidized structure is desired in the matrix. In the former case the metal is cooled through and below the critical range at a rate which will be slow enough to form laminated pearlite and also slow enough to permit the desired degree of graphitization to go on accompanied by the liberation of the desired amount of temper carbon. Such rates may be from 10-100°F. per hr. depending on the metal and the desired properties. The first separation of ferrite in such a heat treatment is usually around the temper carbon producing a so-called "bull's eye" structure consisting of temper carbon surrounded by a ring of ferrite all embedded in pearlite.

Alternatively the metal may be cooled fast enough through and well below the critical range to produce martensite (occasionally only sorbite) and then spheroidized for such a time as will give the desired amount of agraphitic carbon. It is recommended that any metal intended for the manufacture of pearlitic malleable should be moderately low in carbon.

Pearlitic malleable may be made from ordinary malleable either by reheating above the critical point for a time sufficient to saturate all the iron with carbon to a uniform concentration and then proceeding as for the interrupted anneal methods. This procedure is uncommon in practice.

When malleable iron is heated not far above the critical, recombination of carbon takes place first at the grain boundaries. Suitable choice of temperature

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thus permits producing a structure consisting of a network of metal containing agraphitic carbon surrounding ferrite grains. By further heat treatment the network can be made into anything from martensite to granular pearlite. Especially

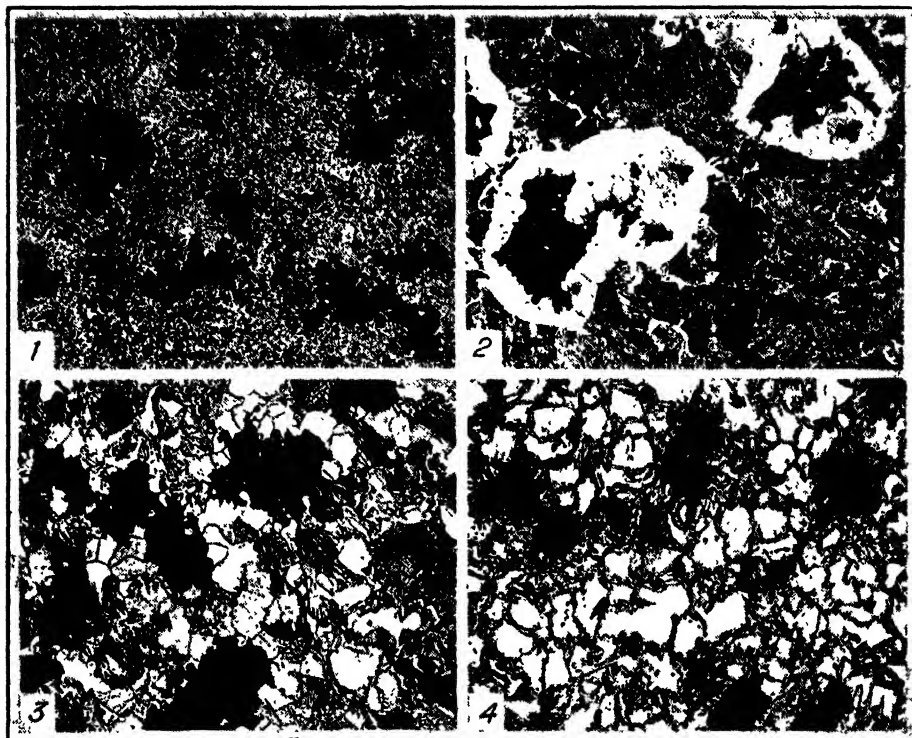


Fig. 1—Temper carbon in spheroidized matrix produced by controlled rapid cooling of high manganese (about 0.75%) white irons completely graphitized to equilibrium above A_1 , followed by spheroidizing draw (100x—nital).

Fig. 2—Bull's-eye malleable produced by normal graphitizing cycle applied to high manganese (about 0.70%) hard irons (100x—nital).

Fig. 3—Granular ferrite and pearlite in high silicon and chromium white iron with normal graphitizing heat treatment (100x—nital).

Fig. 4—Sorbitic carbon at grain boundaries produced by reheating malleable iron just above A_1 then quenching and tempering (100x—nital).

good combinations of strength, ductility and shock resistance are claimed for this distribution of ingredients.

It may be reliably anticipated that all pearlitic malleable is stronger, less ductile and less machinable than malleable itself. It is often less shock resistant but this rule is not without exception. Tensile strengths of 90,000 psi. and perhaps even of over 100,000 psi. are obtainable at a sufficient sacrifice of elongation. Elongation will range downward from that of malleable iron to as low as 2 or 3%, depending upon how much strength was to be retained. The claim is made that spheroidized "pearlitic malleable" is more ductile for a given strength than iron containing laminated pearlite.

The fatigue ratio of all forms of pearlitic malleable is probably near 0.50. The Brinell number may be anything above that of malleable. It is easy to produce metal of a Brinell hardness number well above 300, but machinability usually sets a limit at around 230 and even at 190 machinability is for many products rather difficult.

There has not yet been sufficient critical review of data on the physical properties of these alloys to warrant more definite statements for a handbook.

It has also been found possible to alloy ordinary malleable iron with enough chromium and aluminum to permit of nitriding and it is understood that the product is "pearlitic malleable". This is quite suitable for the purpose for no great ductility would be useful in a nitrified object.

Graphitized pearlitic products of a composition such that they should be classified as derivatives of steel rather than of cast iron have found a few important applications but no systematic survey of that field is yet possible.

Testing of Iron and Its Alloys

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Physical Testing of Tool Steels*

I—Introduction—This article lists and classifies nearly all of the physical tests that might be applied to a tool steel. The practical value of many of them is questionable, but descriptions are included to make available information on all methods.

The object of this article is to help consumers select tests best suited for a given purpose. They should first definitely determine what may be learned from these tests and then choose those most practical and easily correlated with service.

II—Chemical Tests—See page 682 for methods on the chemical analysis of steels.

III—Spark Tests—See page 773 for an article on Spark Testing.

IV—Fracture Tests—The fracture test is a means of examining steel visually for two purposes, (1) To detect internal defects, and (2) to determine fracture grain size. The test will therefore be discussed under these two headings.

1. *Fracture Tests for the Determination of Internal Defects*—This test may be easily misinterpreted by inexperienced observers, so the following guide for proper interpretation is offered.

Fracture of Annealed Steel—Annealed tool steels may be fractured by nicking on one side followed by striking the end close to the nicks with a sledge hammer. The bars or specimens are usually supported on an anvil to avoid danger from flying pieces. The conditions described below may be observed from annealed fractures.

Decarburization—Decarburization is determined by the difference in grain size between outer edges and interior of the specimen. The decarburized zone will exhibit a grain larger in size and brighter in color than the interior of the specimen. All hot rolled bars possess a decarburized surface so that acceptance of material is based on whether the amount present may be detrimental (Fig. 1).

Pipe—Piped steel caused by shrinkage cavities in the ingot will be recognized from an actual discontinuity at or near the center of the specimen. When this condition has been largely removed a coarser or brighter grain may appear in the center (Figs. 2 and 3).

Bursts—Ruptures produced by forging or rolling somewhat resemble pipe. Distinction may sometimes be made from the shape of the defect or from deep etch tests.

Flakes—Flakes will appear as short ruptures or bright spots in longitudinal fractures. When fractures are made through, rather than across the flakes, the bright colored spot will appear somewhat conchoidal in form. Care should be taken not to confuse this defect with areas which have been made bright by rubbing during fracturing or with sections elongated during breakage. Flakes in water hardening steels are usually detrimental. In other types the effect of their presence should be determined before rejection (Fig. 7).

Woody Structure—Fractures taken in the direction of rolling or forging are often of a fibrous appearance. Since all steels are of a heterogeneous nature the degree of such fibrous appearance will depend upon several factors, such as composition, cleanliness; amount, and direction of working. Steels so highly alloyed as to be of a segregated nature; such as high speed steel, will quite often show a fibrous structure to varying degrees, especially in larger sections. An interpretation of the effect of the fibrous structure can only be made with a full knowledge of the general characteristics of the steel in question. Fig. 8 shows a woody structure.

Fractures of Heat Treated Steels—Heat treated specimens may be nicked with thin cut off wheels to assist in obtaining satisfactory breaks. When breaking, precaution should be taken to prevent injury from flying fragments. Any of the conditions encountered in the fractures of annealed steel can be recognized to better advantage in heat treated specimens. It is often preferable in examining heat treated fractures for internal defects to cut a relatively thin disc and break this in the direction of rolling or forging so that the defects are examined in the elongated condition.

Penetration of Hardness—The penetration of hardness in carbon or low alloy steels may be determined by the variation in grain size from surface to center in

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stots, Chairman; A. S. Jameson, A. J. Scheid, Jr., G. V. Luerssen, W. H. Willis, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadie, O. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

transverse fractures. A more certain method of measuring penetration is by grinding and etching the cross section of the piece. Tests of penetration are taken up more in detail in Section VIII in which illustrations are shown on both fractured and deep etched sections.

2. *Fracture Tests for the Determination of Grain Size*—In the annealed condition,

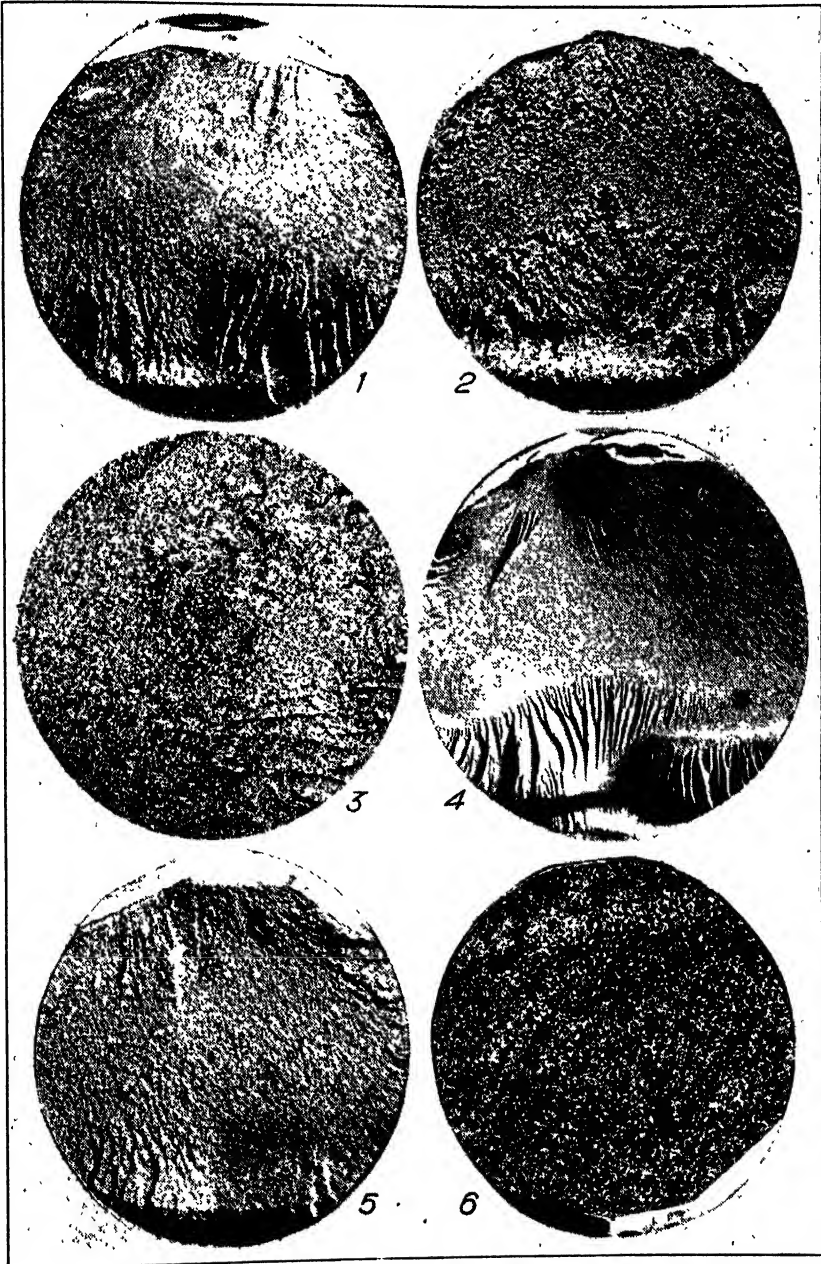


Fig. 1—Decarburized surface. Fig. 2—Pipe. Fig. 3—Coarse center grain result of pipe. Fig. 4—Proper grain for high speed steel. Fig. 5—Fine grain carbon steel. Fig. 6—Coarse grain.

highly alloyed steels show a finer grain than carbon or low alloy steels as shown in Fig. 4, 5 and 6.

The grain size in the treated condition will vary with the type of steel as regard composition, inherent characteristics, the hardening temperature, time, and the quenching medium.

The visual grain size in a fracture is usually a reliable indication of the correctness of heat treating. However, there are exceptions especially in high speed steels, so the fracture test should be supplemented by microscopic examination (Section VII).

The arbitrary standards are generally used for the quantitative determination of fracture grain size. These standards consist of fractured $\frac{1}{8}$ in. dia. test samples, each uniform throughout its section, and numbered from 1 to 10, number 1 being an extremely coarse fracture, ascending numbers becoming finer grained in uniform steps, 10 being extremely fine and silky. Fracture grain sizes for No. 1, 5, and 10 of these standards are shown in Fig. 9.

Fracture grain size readings are made by comparing the unknown fracture with the standard and designating its grain size as the number of the standard fracture which it most nearly matches. If the unknown fracture falls midway between two of the standards such as for instance 8 and 9, it is rated as a half number, such as 8½.

V—Hardness Testing
—Descriptions of the Brinell, Rockwell, Scleroscope, Monotron, Vickers, and file hardness testing methods, as well as Hardness Conversion Data, are given on pages 112-128.

For testing medium and low hardness tool steels, those machines using the principle of ball impression are preferable, while for testing high hardness tool steels, the diamond point machines are generally used. The file test is used on hardened tool steels only.

V-a—Hardness Testing at Elevated Temperatures—See p. 129 in this Handbook, for an article on this subject.

VI—Macro Etching of Tool Steels—Procedure for deep etch testing is given on

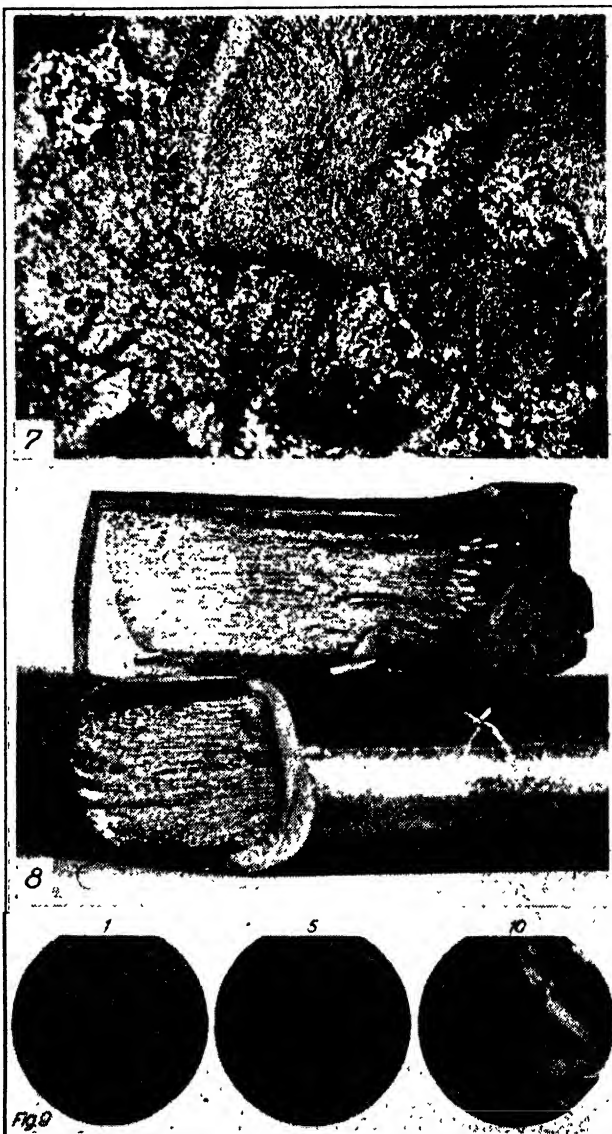


Fig. 7—Flakes. Fig. 8—Woody structure. Fig. 9—Fracture grain sizes for specimen 1, 5, and 10, X5.

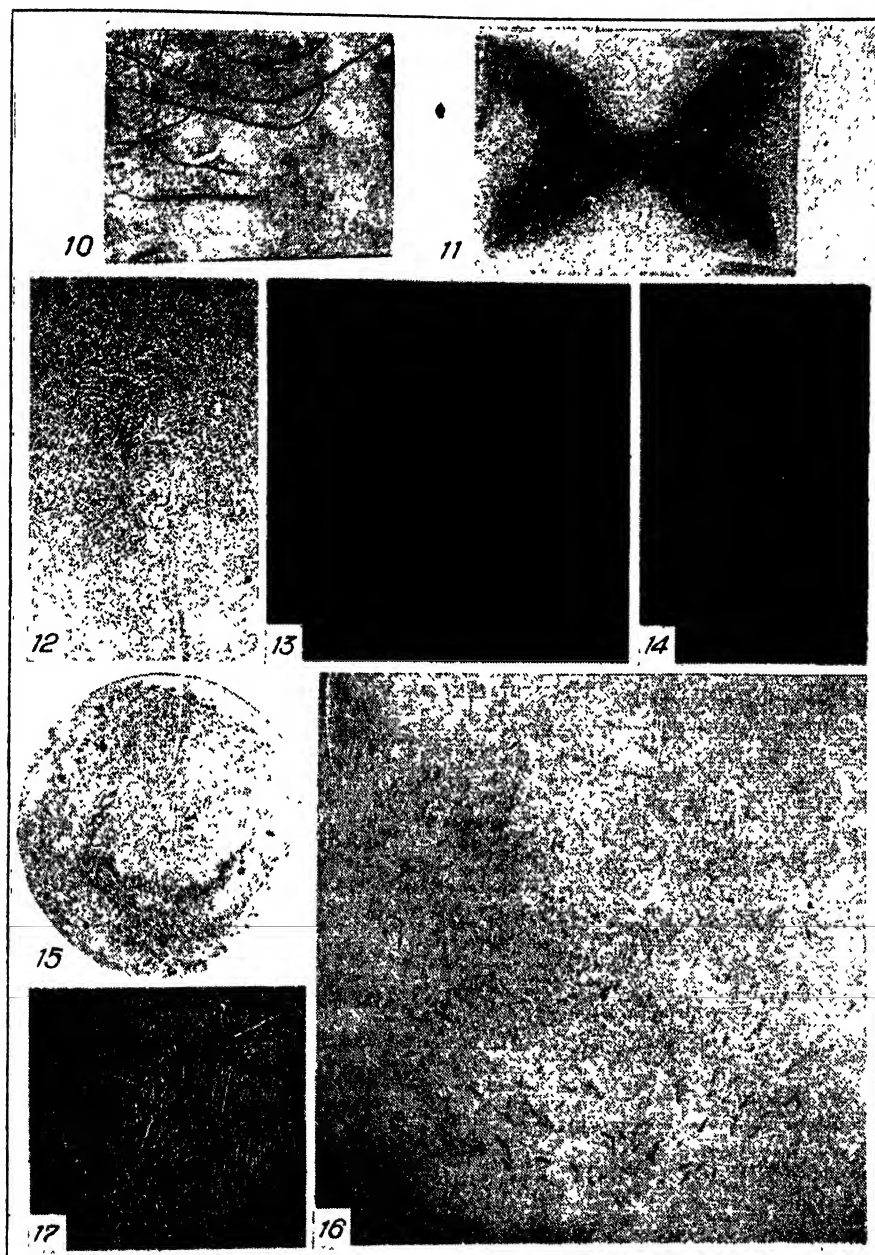


Fig. 10—Etching cracks. Fig. 11—Surface appearance and pattern effect. Fig. 12—Center porosity. Fig. 13—Pipe after etching. Fig. 14—Hammer burst after etching. Fig. 15—Unsond steel—blow holes and nonmetallic inclusions. Fig. 16—Internal cracks. Fig. 17—Dendritic structure.

page 726, consequently, this article will deal strictly with interpretation of the results rather than procedure.

The deep etch test reveals readily and quickly many of the characteristics of tool steel, but in some instances, further examination by standard testing methods is required to evaluate them properly. The knowledge that a piece of steel is dendritic or contains metallic and nonmetallic segregates is not sufficient evidence in itself on which to base definite conclusions of the properties of the steel. There is real value in the deep etch test when used to separate materials which are obviously defective from those which are not. It is easily made, but requires experience and judgment to interpret the results.

Cracks from Etching—Hardened or otherwise highly stressed steels should be sufficiently tempered before etching to prevent cracking because they may crack in the etching solution (Fig. 10).

Surface Appearance—Steels may etch with a comparatively smooth surface or with a highly rough or pitted surface, depending upon variables in manufacture, and composition. Therefore, a highly roughened surface is not necessarily detrimental (Fig. 11).

Irregularity in pitting may usually be attributed to one or more of the defects given below. Certain manganese, oil hardening types are more readily attacked by

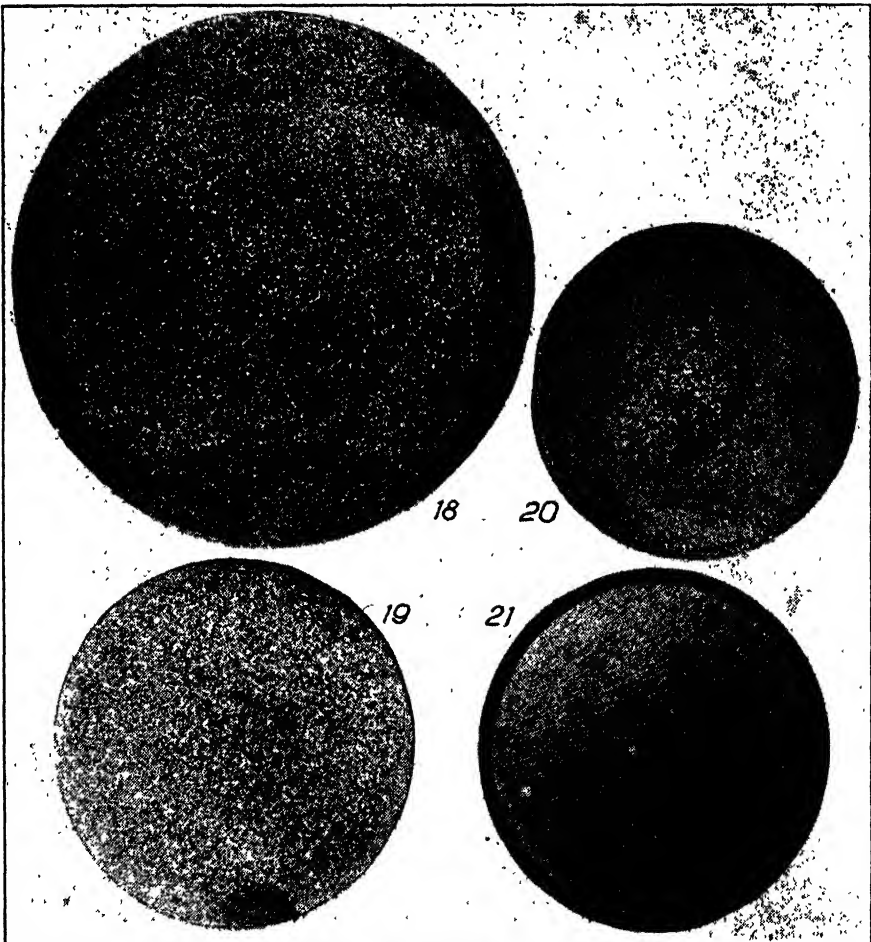


Fig. 18—Pattern effect. Fig. 19—Coarse grain size as shown by etching. Fig. 20—Decarburization as shown by etching. Fig. 21—Hardened case shown by etching 1% carbon tool steel.

the acid and are often decidedly roughened without in any way being defective.

Center Porosity—Porosity may be the result of an actual discontinuity within the metal, in which case it is probably more proper to classify the defect as a pipe. Usually, however, the porosity is of such a nature that it is not visible until the specimen has been subjected to the etch. This condition can be found in widely varying degrees and the question of whether the steel should or should not be used is one of experienced judgment (Fig. 12).

Pipes and Bursts—Usually such defects are visible before deep etching. After etching it is often possible to distinguish between the two by the degree of sponginess surrounding the defect. Piped material usually shows considerably more sponginess than burst material (Fig. 13 and 14).

Unsound Steel—Numerous blow holes and nonmetallic inclusions visible as the result of the deep etch are usually indicative of both gases and oxides being distributed throughout the steel at the time of casting (Fig. 15).

Nonmetallic Inclusions and Metallic Segregates—In killed steels, nonmetallic inclusions usually appear as pits and must not be confused with pits occurring from the etching out of metallic segregates. When nonmetallic inclusions are suspected in highly alloyed steels which may contain metallic segregates, a comparison should be made of an annealed specimen and a hardened specimen etched alike. If the etching pits are the result of nonmetallic inclusions they will appear similarly in both the annealed and hardened specimens; if they are the result of a metallic segregate they will differ. Microscopic examination is preferable for determining their true character.

Internal Cracks—Internal cracks, sometimes called flakes or cooling cracks, can often be observed as the result of the deep etch test. These cracks are an actual discontinuity in the metal and, depending on their nature and distribution, may make the steel unfit for use (Fig. 16).

Dendrites—Etching often reveals a dendritic structure, which is the result of the crystallization characteristics of the ingot. Dendritic structure is not detrimental in most instances. The permissible degree depends on the application (Fig. 17).

Pattern Effect—Pattern effect is almost wholly the result of the crystallization of the ingot and generally results from that part of the bar which was the columnar structure of the ingot etching differently from that part which was the granular structure of the ingot. Should the steel contain considerable sulphide and silicate inclusions, then the area of contact between the columnar structure and the granular structure may be particularly noticeable. In the absence of large amounts of sulphides and silicates, the pattern effect probably is of no serious consequence (Fig. 18).

Grain Size—While the etch test is of no definite value in determining grain size, nevertheless the manner in which many specimens etch may indicate something of the grain size. Generally the larger the grain, the coarser will be the appearance of the etched surface (Fig. 19).

Decarburization and Carburization—Generally the areas which have been either decarburized or carburized will etch differently from the remainder of the specimen, chief difference usually being one of color. Decarburized parts will appear lighter in color and carburized parts darker (Fig. 20).

Hardened Case—In shallow hardening steels a contrast in color results between the case and the core by mild etching (Fig. 21).

Flow Lines from Forging or Rolling—A longitudinal section when subjected to the macro etching will often show flow lines due to the elongating of structural constituents. Such flow lines are always visible to a greater or less degree. They indicate the directions in which the steel was worked. Flow lines do not signify defective material (Fig. 22).

Surface Defects—Seams, laps, and cooling cracks, and other surface defects are revealed and exaggerated in the surface of bars which have been deeply etched (Fig. 23). Therefore, a short time etch is recommended.

Soft Spots—Soft spots which so often result when hardening carbon or low alloy tool steels can be readily distinguished by the macro etch test. The soft spots invariably etch in relief and are not so dark in color as the harder surrounding areas (Fig. 24).

Grinding Cracks—Grinding cracks can be easily distinguished by the standard macro etch and are usually identified by a pattern of some symmetry (Fig. 25).

VII—Microscopic Test—The examination of polished sections of tool steel under

the microscope is a common method used in connection with its inspection, the investigation of tool failures and various research problems.

Cutting, grinding, and polishing equipment required for this work is covered under "Preparation of Metallographic Specimens," on page 722. Etching reagents are given on page 170.

The avoidance of polishing pits and scratches in tool steels is not so difficult as with soft steel. Polishing pits are sometimes mistaken for inclusions and careful polishing is essential for best results. For the etching of tool steel specimens, the use of a 2-5% solution of nitric acid in alcohol is generally applicable. Somewhat stronger solutions may be used for highly alloyed types.

In the microexamination of tool steel, a microscope with a capacity up to 1000 diameters should be satisfactory for all ordinary requirements.

By examination under the microscope, it is possible to determine a number of factors which may affect the quality or performance of tool steel. Among these may be mentioned:

- | | |
|------------------------------|---------------------------------------|
| (a) Grain size | (d) Size and distribution of carbides |
| (b) Effect of heat treatment | (e) Nonmetallic inclusions |
| (c) Structural constituents | (f) Segregations |

(a) *Grain Size*—The grain size may be considered as referring to the size of the austenite crystals which are formed when the steel is heated above its critical



Fig. 22—Flow lines on longitudinal section. Fig. 23—Surface defects—rolling laps. Fig. 24—Soft spots. Fig. 25—Grinding cracks on hardened die steel.

points. These grains may be observed under the microscope in steels that can be made austenitic at room temperatures. It is possible by certain heat treatments to develop grain structures that are a record of the austenite grains that existed at the previous high temperature to which the steel was subjected. (Fig. 26 and 27.) The well known McQuaid-Ehn test is a method for the study of the grain size under a given set of conditions. It is usually limited to carbon or low alloy steels and grain size observed for comparison with a standard or chart by examination of the case at 100-150 diameters. Grain size, factors affecting it, and its relation to physical properties are of importance with some users of carbon and low alloy tool steels.

(b) *Effect of Heat Treatment*—While the most common method of checking the prior heat treatment of tools is by the examination of hardened fractures, microexamination of hardened structure is more accurate. In cases of steels

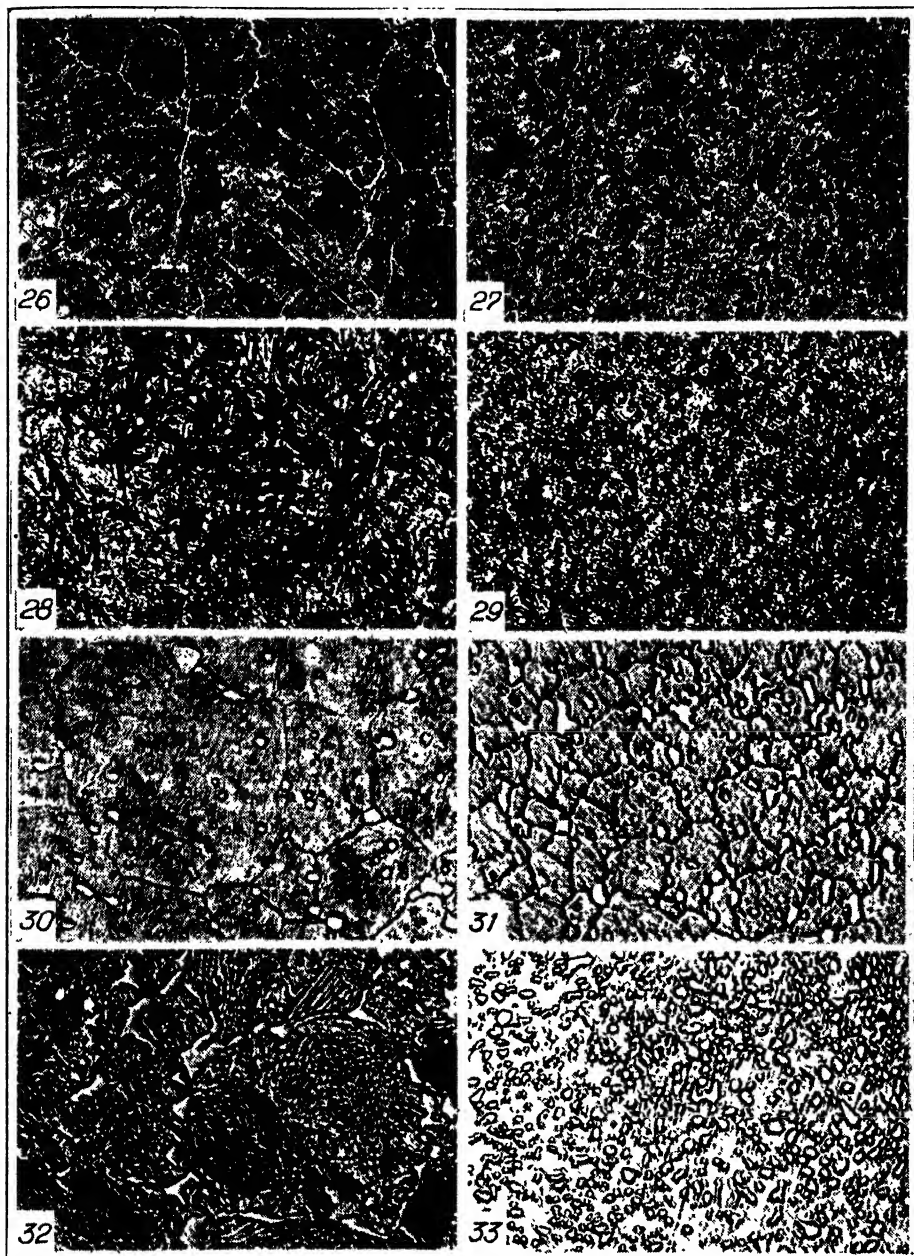


Fig. 26—Case structure of coarse grained carbon tool steel (0.90% C). Carburized at 1750°F. So-called normal steel. 125X. Fig. 27—Same as Fig. 26, but of so-called abnormal steel. 125X. Fig. 28—Large martensitic needles in overheated manganese oil hardening tool steel. 600X. Fig. 29—Same as Fig. 28, but properly hardened. 600X. Fig. 30—Large austenitic grain size from over heating high speed steel when hardening. 660X. Fig. 31—Normal austenitic grain size in hardened high speed steel not tempered. 600X. Fig. 32—Carbon tool steel (1.20% C). This steel was not fully annealed so shows lamellar pearlite and traces of segregated cementite. 600X. Fig. 33—Same as Fig. 32, but fully annealed with carbides in a spheroidized condition.

developing a largely martensitic structure when hardened, the size of the martensitic needles may be considered a measure of the austenitic grain size following a given heat treatment. A structure with enlarged martensitic needles is associated with overheating (Fig. 28). On the other hand, partial or complete absence of martensite and the presence of numerous small undissolved carbides may indicate an underheated condition. The relative proportion of austenite, martensite, and troostite sometimes throws light on the degree of tempering (Fig. 29).

Properly hardened or overheated high speed steel as quenched from the usual hardening temperatures and high carbon, high chromium steels when overheated develop an austenitic structure. Observation of the size of the austenitic grains is useful when investigating the heat treatment or physical properties of these types (Fig. 30 and 31).

(c) *Structural Constituents*—A large proportion of tool steels have a comparatively high carbon content and represent eutectoid or hypereutectoid compositions. In such steels, carbide forms predominate as the structural constituents. These may refer to pearlite, cementite, austenite, martensite, troostite, sorbite or carbide segregate (Fig. 32). Ferrite may exist as a minor constituent in the lower carbon (hypoeutectoid) tool steels. It also is the principal constituent of the matrix observed in the examination of the structure of annealed tool steels when the carbides are present in the spheroidal condition (Fig. 33).

It may be desired to identify or estimate the proportion of structural constituents of tool steel in the annealed and hardened condition and sometimes in the hot worked condition. This work is done by the examination of longitudinal or cross sections at usually 500 diameters or more.

(d) *Size and Distribution of Carbides*—In hypereutectoid carbon tool steels and the more highly alloyed tool steels, such as high speed and the high carbon, high chromium types, size and distribution of the carbide segregate have a bearing on quality and may be a factor in tool failures. It requires considerable experience on the part of the observer to know what to expect as to uniformity and what is objectionable as to carbide network and segregation in various sized sections. Inspection for carbide *distribution* is made at about 100 diameters (Fig. 34, 35, and 36). *Size* of carbides in alloy or carbon tool steels is preferably observed at 500 diameters or more.

(e) *Nonmetallic Inclusions*—Among the nonmetallic inclusions that may exist in tool steels are slag or refractory inclusions, and others that represent deoxidation products and various silicates.

Examination for nonmetallic inclusions may be made by examining unetched polished longitudinal sections at 100 diameters or more. In some cases when the steel tends to pit readily in the polishing, inclusions show better if polished in the hardened condition and after the specimens are lightly etched in nital (Fig. 37).

(f) *Segregations*—Carbide segregation is the most common kind that may exist in tool steels. It exists in varying degrees in the highly alloyed types such as high speed, and high carbon, high chromium steels as referred to under paragraph (d) above, covering carbide distribution. Carbon and the low alloy tool steels may show carbide segregation to a lesser extent. Excessive carbide segregation is objectionable as it may be a cause of tool failures or difficulty in machining. Carbide segregations may be observed to advantage by the examination of longitudinal sections at magnifications of 200 diameters or more.

VIII—Hardening Tests—In devising and interpreting tests for the hardening characteristics of tool steel, it is important to consider the type of steel, its application and method of hardening employed.

1. *Penetration of Hardness, Shallow, and Medium Deep Hardening Steels*—Penetration of hardness is the depth to which a tool steel will show full hardness upon quenching. The carbon and carbon-vanadium steels are typical shallow hardening and the line of demarcation between the hard case and the relatively soft core being quite distinct. Starting with the carbon steel increasing hardness penetration can be obtained by the addition of small amounts of such elements as chromium, manganese, silicon and molybdenum. As the hardness penetration is increased by the addition of such elements, the line of demarcation between the case and the core grows less sharp, and in the extremely deep hardening steel is replaced by only a slight drop in hardness toward the center.

Tests for penetration are of most value in connection with the shallow and medium deep hardening types. Because of the wide difference in behavior of these types, no single test can be adapted to all. Consequently two types of test, one

for shallow hardening, and one for deeper hardening steels are here suggested.

For the shallow hardening types a very convenient test is the P-F test (Penetration-Fracture). This consists of hardening in brine four samples machined to $\frac{1}{4}$ rd. x 3 in. long, one each from 1450, 1500, 1550, and 1600°F., notching each in the middle and fracturing by impact. Then one-half of each piece is examined for the grain size of the case, by comparison with the standard described under Section IV. Penetration tests are made on the other half of each sample by grinding the fracture and smoothing it on No. 0, or finer, abrasive, etching three minutes in 1-1 HCl at 180°F. and measuring the hardness penetration in 64ths of an in.

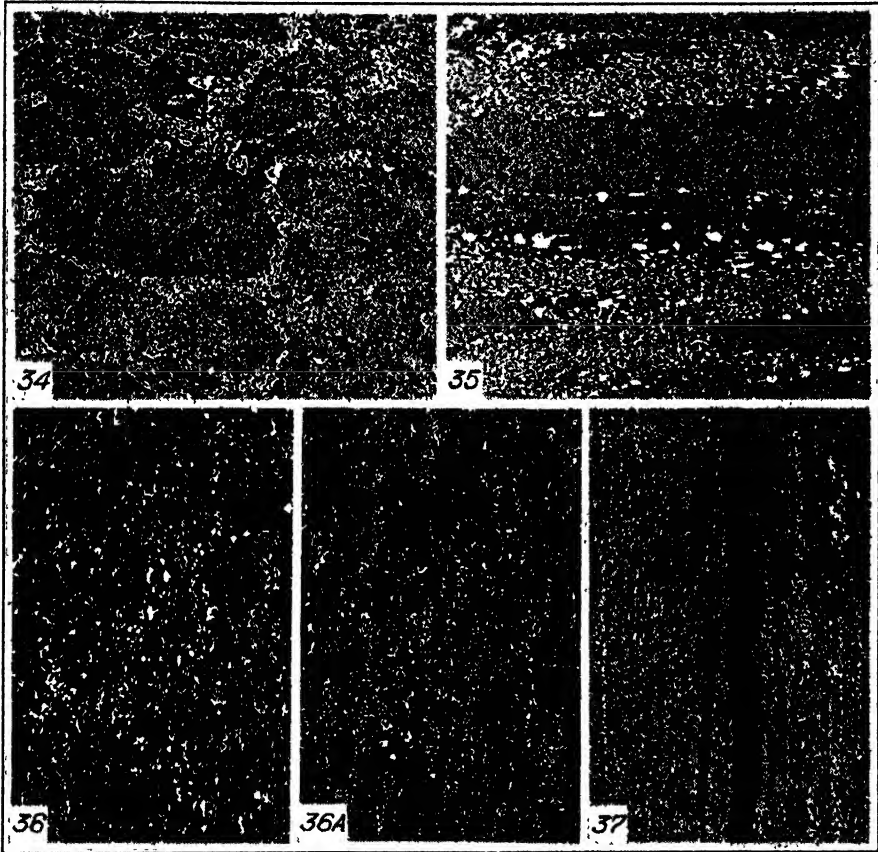


Fig. 34—High speed steel with cellular carbide distribution. The original ingot structure was not fully broken up during hot working. 125X. Fig. 35—High speed steel with heavy carbide segregation. 125X. Fig. 36—Uniform carbide distribution in high speed steel. From section $1\frac{1}{2}$ x $\frac{1}{4}$ in. Bar stock. 125X. Fig. 36A—Same as Fig. 36, but from a 3x3 in. hob forging. 125X. Fig. 37—Large nonmetallic inclusion in high speed steel. 125X.

The P-F characteristic is then recorded as numerals. The first four numbers represent the penetration in 64ths, and the last four numbers the fracture grain size. The first number of each group represents the P-F results for a temperature of 1450°F. and the second number of each group represents the P-F for a temperature of 1500°F., and so on. Fig. 37A illustrates a typical test, the figures designating the penetration and fracture values determined for each specimen. The value of this test in showing the hardening characteristics of a plain carbon steel over a wide range of temperature is obvious.

Various precautions must be taken in conducting this test where results are to be strictly comparable. The original structure of the test pieces resulting from annealing or pre-treatments is important. For general comparisons, since most tools are made and hardened from an annealed bar, it is desirable to make the

test on annealed specimens, just as cut from the bar stock. If, however, it is the practice of the consumer to normalize or in some way pre-treat the tools before final hardening, the P-F tests should be made on specimens having these preliminary treatments in order to give an indication of the behavior in the finished tool.

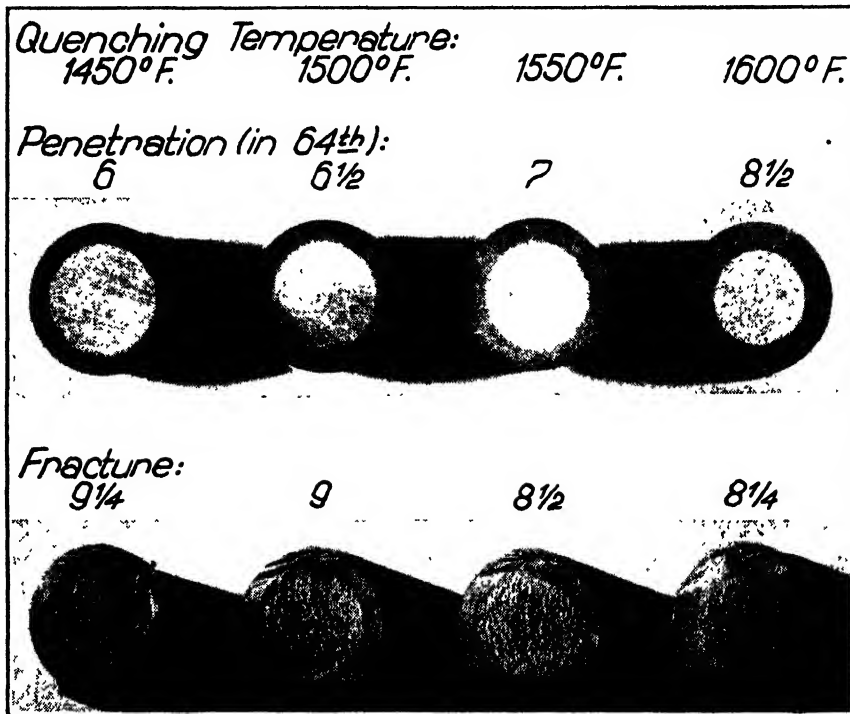


Fig. 37A—Etched sections and fractures in P-F test on carbon steel.

For accurate results close control of the time cycle and temperature in hardening must also be maintained. Usually the specimens are so heated that the total time in the furnace is 25 min. for each temperature. These conditions can be realized with considerable uniformity by using a relatively large furnace, bringing it up to the final desired temperature, introducing the specimens and bringing them up to temperature without allowing the furnace to drop back.

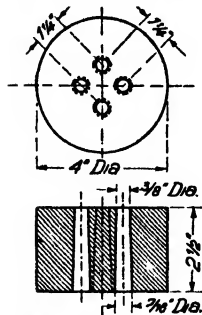


Fig 37B—Block used in determining penetration for deep hardening steels.

For uniform results specimens should be quenched in a flush using 10% brine and a suitable vertical jig.

2. *Penetration of Hardness, Deep Hardening Steels*—For determination of penetration on the deeper hardening steels, the $\frac{3}{8}$ in. dia. specimen employed in the P-F test cannot be used since this section would harden entirely through. The heavy sections necessary for testing these steels present considerable difficulty in cutting. Consequently the following methods using small specimens inserted in a larger block to simulate the larger mass have been suggested and used. However, they are not well established or as standardized as the method described above.

The first method consists of a disc of ordinary soft steel approximately 4 in. in dia. x $2\frac{1}{2}$ in. thick is used as the block. Four equally spaced holes are drilled longitudinally through this disc and tapered slightly so that corresponding tapered plugs of the steels to be tested can be inserted. A suggested assembly of the disc and the test specimens is shown in Fig. 37B.

After the test plugs have been driven in, the entire fixture is heated to the quenching temperature of the steels under test, and quenched. Plugs are then removed, two flat areas are ground longitudinally on opposite sides and Rockwell determinations made every $\frac{1}{2}$ in. from one end to the other. From these readings a penetration curve can be plotted as shown in Fig. 37C.

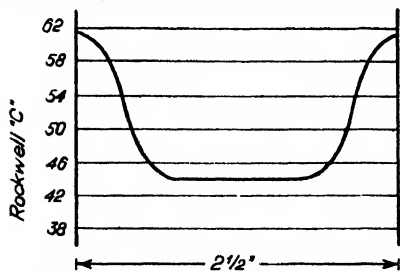


Fig. 37C—Hardness penetration curve on deep hardening steel.

disc between two cylinders of equal dia. The assembly may be held together by a bolt through the center, in which case it is necessary that one of the cylinders and

The second method for determining the penetration of deep hardening steels, and one which may be used to advantage in studying the effect of heavier mass upon the penetration characteristics of the shallow hardening steels, consists of cutting a disc of the steel to be tested measuring approximately $2\frac{1}{2}$ in. in dia. x $\frac{1}{2}$ in. thick, grinding the two surfaces of this disc exactly parallel, then clamping the

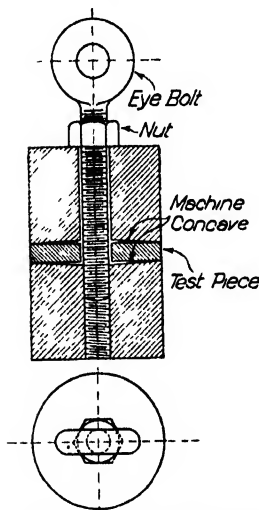


Fig. 37D—Jig for determining hardness penetration on thin disc, and for studying effect of mass.

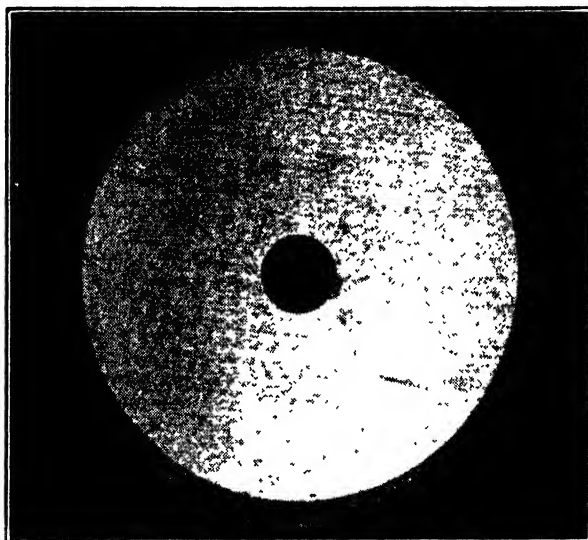


Fig. 37E—Test piece shown in Fig. 37D after etching.

test piece be bored axially and the other cylinder tapped to accommodate this bolt. The entire assembly is then heated to the temperature desired, properly quenched and the test piece removed from the fixture. The test piece may then be etched to show penetration, or Rockwell hardnesses may be taken over the face, which will have the same characteristics with regard to hardness as if a whole bar of the same size had been quenched and cut in half. The fixture with test piece engaged, and the test piece after removing and etching are illustrated in Fig. 37D and 37E.

3. Degree of Hardening—To test the degree of hardening, the samples described under "Penetration of Hardening" may be used and the hardness read by the usual methods (See Section V—Methods of Hardness Testing).

4. Uniformity of Hardening—Soft spots are peculiar to tool steels of the shallow hardening type, due to improper quenching conditions. Misleading information will be developed if standardized methods of quenching are not employed in making a test to determine the uniformity of hardness in these steels.

A hardened sample, tool, or part, may be tested by etching the polished surface with hot 1:1 HCl or 10% HNO₃ in alcohol at room temperature. Areas of variable hardness will etch light or dark and may be explored by standard hardness testing methods.

5. Susceptibility to Hardening Cracks—A number of tool steels are susceptible to hardening cracks, due to composition, prior treatment or variables of manufacture. In determining this characteristic in steels of similar chemistry, it is important that a standardized temperature, time of heating and quenching cycle

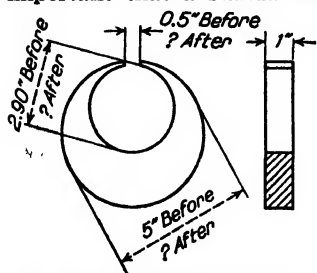


Fig. 38—Navy specification for deformation.

be employed. To locate hardening cracks, a properly hardened sample, tool, or part may be examined magnetically as described under "Magnetic Testing," on page 770. An alternate method involves the etching of the piece in hot 1:1 HCl, 10% HNO₃ in alcohol or 10% solution of ammonium persulphate in water, at room temperature.

6. Sensitivity to Grain Growth—Difference in sensitivity to grain growth may be observed in tool steels when heated in increasing intervals above the critical. This characteristic is dependent on composition, variables of manufacture and heat treatment.

A simple test involves the hardening of test pieces (as described under "Penetration of Hardening"), over a range of ascending temperatures, starting with the normal or customary hardening temperature for a given lot of steel. For example, samples of 1.00% carbon steel are hardened at 1400, 1450, 1500, 1550, and 1600°F. in water. The pieces are fractured, compared with a standard, or examined microscopically.

7. Susceptibility to Soft Surface—A susceptibility to soft surface is peculiar to several types of tool steel. Differences between types may be determined by hardening samples of the respective lots from their normal quenching temperatures, after which accurate hardness tests may be made. In testing steels of similar chemistry, it is important to employ a standardized temperature, correct furnace atmosphere, time of heating and quenching procedure. The depth of the soft surface may be measured by a repeated cycle of uniform grinding and hardness testing.

IX—Machinability—Method for Testing for Machinability—The only practical test for machinability is one based on actual machining operations.

Machinability is not a definable property of tool steel because "machining" may involve a dozen or more different operations such as turning, tapping, reaming, drilling, broaching, threading, or backing-off. Each of these different operations is further complicated by the requirements of the job. For example, milling of the flutes in a tap might require that no burr be thrown up on the teeth, while no such requirement would be imposed on milling the flutes on a reamer. Drilling large holes does not involve the same problem as drilling small holes, and gun barrel drilling introduces still other problems. A delicate backing-off operation may dominate all other machining requirements in making certain tools.

Each user must therefore, determine the condition in the tool steel which produces best machinability for his own particular purpose. Certain tests can be decided upon, including analysis, hardness, and microstructure, which can reasonably be expected to reproduce the machinability which is desired. For any given analysis of tool steel, incoming material can be inspected for machinability by testing the hardness and microstructure and comparing them with standards which have been approved for satisfactory machinability.

X—Testing of Tool Steels for Nondeforming Qualities—All tool steels tend to distort during heat treatment. This distortion is affected by the rate of heating, rate of cooling, design of the part, and by characteristics of the steel. Obviously, in any attempt to compare steels for nondeforming qualities as affected by steel characteristics, control over all other variables must be maintained.

There should be no difficulty in maintaining uniform rates of heating for test specimens. Rates of cooling will naturally vary with the type of steel since some steels must be hardened by quenching in water or brine, others in oil, air blast, or still air. This rate of cooling, however, should be uniform when comparing different makes of steel of the same type.

The degree of hardness resulting from treatment is also important since a steel hardened to a low hardness will move less than the same steel treated to a high hardness. While uniform rates of heating and cooling should control this to some extent, a standard range of hardness for various types of steel should be used.

Numerous designs of test specimens are possible and the observer should select that standard design which most nearly meets his requirements. The following four designs are suggested:

1. Machine a section of annealed steel to $\frac{3}{4}$ in. round \times $3\frac{1}{2}$ in. long. After machining, the specimen should be given a strain relieving treatment by heating to a temperature just below the critical, followed by slow cooling. It should then be ground and accurately measured for length and diameter. A standard heat treatment should be used. The dimensions may be rechecked before and after tempering if desired.

2. A ring $2\frac{1}{4}$ in. outside dia. \times $1\frac{1}{4}$ in. inside dia. \times $\frac{3}{4}$ in. thick may be prepared and handled in the manner of specimen No. 1.

3. Flat specimens at least 6 in. square \times $1\frac{1}{2}$ in. thick are especially valuable as an indication of the movement that may occur in steels used for large dies. In this test the specimen may be prepared as described above but the measurement involves checking the face of the specimen for flatness to determine the extent to which the surface has become convex or concave.

4. Fig. 38 illustrates a specimen of nonuniform section sometimes used for movement tests. Preparation of this specimen should be similar to that suggested for test No. 1. The accuracy of this test is doubtful because of the greater effect on the movement exercised by slight changes in rates of heating and cooling.

XI—Tensile Tests at Room Temperature—The tensile properties of tool steel in the annealed condition are of little commercial value, and when tested in the hardened condition, the tensile determination presents considerable difficulty. It is possible to obtain tensile properties that do have some value by tempering to such a hardness that the steel will have appreciable reduction of area and elongation, which for many tool steels is in the vicinity of 40 Rockwell C.

When determining the tensile properties of tool steel, a specially designed test specimen is recommended (Fig. 39). In order to secure perfect alignment, special grips using the ball and socket principle are recommended.

The specimens are usually heat treated in test bar size but leaving about 0.020 in. on the diameter to permit removal of decarburized surface and correct for warpage.

XI-a—Tensile Tests of Tool Steels at Elevated Temperatures—The Joint Committee of the A.S.T.M. and the A.S.M.E. have prepared tentative standard methods* for tensile tests of steels at elevated temperatures. These methods are satisfactory for medium or low strength steels, but for high strength steels it is difficult to obtain accurate results without some modifications.

The Elevated Temperature Tensile Test Specimen—Fig. 40 shows a satisfactory form of test specimen. The best practice is to rough turn in the annealed condition; heat treat; and grind as indicated. In the case of high strength steels with low elongations, best results will be obtained if the ends are tempered for a short time in a liquid bath, previous to grinding.

The diameter of the specimen (gage length section), may be varied from the dimension shown in Fig. 40 to as small as 0.200 in. with satisfactory results. When a smaller specimen is used, the gage length should equal four diameters so that the elongation values will be directly comparable to those of the standard specimen. The detail dimensions of a small specimen are shown in Fig. 41.

Gage marks can be put on the hardened specimens conveniently with the diamond point hardness tester. Wash the surface with a copper sulphate solution where the gage marks are to be placed, then scribe the 2 in. gage length with sharp dividers and follow by prick punching or use the diamond point. If an extensometer is to be attached to the specimen, it is necessary to put gage marks on opposite sides. This procedure is much facilitated by rotating on centers and using the dividers against a rest while laying off the gage length.

The Testing Equipment—Various forms of shackles may be used to grip the ends of the specimens. A satisfactory form is shown in Fig. 42. This type is readily adapted to both the threaded-end and the shouldered-end types of specimens. The split adapters that fit the ends of the shouldered-end specimens are strengthened by the solid rings which have a tapered bore so that they can be wedged on the adapters after the specimen is inserted. Another satisfactory form for shouldered-end specimens is shown in Fig. 42a.

The best furnace for making high temperature tensile tests is a differentially

*See A.S.T.M. Proc., 1934, v. 34, pt. I, p. 1214 (E21-34T and E22-34T).

or gap wound resistance type of electric furnace with particular attention given to baffling, insulation, and tightness so as to prevent temperature gradients either in the specimen or the adjoining shackles. For short time, elevated temperature tensile tests manual control of the temperature is generally adequate, but for the long time or creep tests automatic control becomes mandatory. In any case, it is essential to know the actual temperature of the specimen and maintain this temperature throughout the reduced portion at each temperature used.

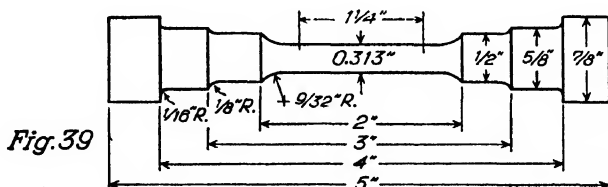


Fig. 39

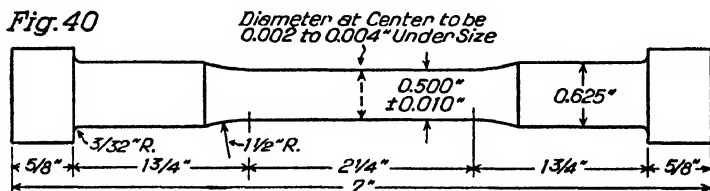


Fig. 40

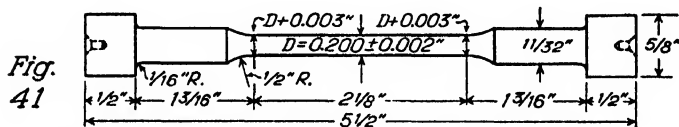


Fig. 41

Fig. 39—Special tensile test specimen for tool steel. The ends may be square or ball-shaped. Fig. 40—Tensile test specimen for tool steel at elevated temperature. Fig. 41—Same as Fig. 40, but where a small specimen is required.

The use of the extensometer in high temperature work makes the maintenance of uniform temperatures so difficult that the best results are often obtained by compromises between heating equipment and deformation measuring apparatus. The use of the smaller sizes of specimens assist in obtaining uniform temperatures throughout the specimen.

Self-aligning shackles are quite essential. The usual method is to provide ball and socket joints at the ends of the shackles where they are attached to the heads of the testing machine as indicated in Fig. 42.

Testing Procedure—It is particularly important in short time high temperature tensile tests to heat slowly for consistent results. Many of the published discrepancies are due to too fast a heating rate. The elastic properties of tool steels as usually determined, such as elastic limit, proportional limit, and frequently Young's modulus, are of questionable value because of creep phenomena at the higher temperatures and the difficulties contingent upon their determination. Better results will be obtained by the use of yield strength values based on some arbitrary permanent set, or perhaps two different permanent set values such as 0.1% and 0.2%, following the methods given in the standards of the A.S.T.M. (E8-33). Such yield strength values need be used only in the absence of a well defined yield point in the steel, but most tool steels have no well defined yield points.

Temperatures are best obtained by clamping thermocouples directly on the shoulders adjacent to the gage length of the specimen. Shield the hot junctions from heat of the furnace walls by placing asbestos paper over the junctions before applying the clamps. Additional thermocouples in the furnace atmosphere and shackles may assist in obtaining and controlling the desired temperatures, but generally are not reliable for measuring specimen temperatures.

In reporting results, the details of the specimen apparatus and procedure should be given in addition to the composition and history of the material.

XI-b—Tool Steel—Compression Testing—The object, generally, of compression testing is to determine stress and deformation under load, and the load necessary to produce failure.

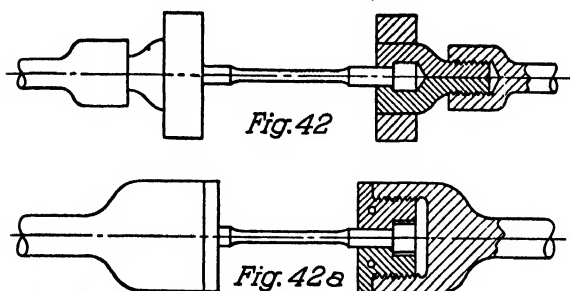


Fig. 42 and 42a—Types of shackles used to grip ends of tensile specimen.

For tool steel, the latter information is all that is usually required. The test is used mostly in connection with problems of tool design, or in comparison of one type of steel with another, or one heat treatment with another. The material is tested in the hardened condition.

Fig. 43 and 44 show types of specimens which have been used. The form shown

by Fig. 44 is usually preferred. The method of carrying out the test is illustrated by Fig. 45. The following precautions are essential:

1. One bearing block must be provided with a spherical seat.
2. The specimen and bearing blocks must be accurately centered on the table of the machine so that the line of pressure will pass through the axis of the specimen, bearing blocks, and testing machine.
3. Apply the load at a uniform rate, generally less than 0.02 in. per min.
4. Full protection from flying pieces must be provided.

The drop of the beam or dial pointer is usually taken to indicate ultimate failure. It is recommended that the test be stopped at this point. The load at rupture may be somewhat higher, but is considered to be without significance due to the radical change in shape and dimensions of the test piece. For more complete particulars, see references 1, 2, and 3.

For measuring the resistance of a superficially hardened object to local crushing or sinking under load, two methods have been used. The first makes use of a plain cylindrical hob which is pressed into the object to be tested, using suitable increments of load. After each increase of load has been applied, the hob is removed and the piece examined. The load at which the first signs of permanent sinking occur, is taken as an indication of the local carrying capacity of the surface. In the second method, described by O. W. McMullan¹ special Brinell balls, preferably of the hard carbide variety are pressed into the surface to be tested under increments of load, the impressions being measured in the usual manner.

XII—Impact Tests—The standard impact tests as described on page 50 are not commercial tests for tool steel, as the values obtained mean little in the annealed condition and when testing is done in the hardened condition, the values are too erratic.

When this type of testing is used the design of the test bar may be varied according to the characteristics of the steel.

The test bars are highly stressed and care is necessary to prevent injury from the flying fragments during the impact testing.

The torsion impact test is comparatively new for developing information on tool steel harder than Rockwell C 60. The full significance of the test and its results must await further developments.

XIII—Torsion Test as Applied to Tool Steels—The problem of determining accurately some of the fundamental properties of hardened tool steel is difficult in that exceptionally high strengths and low degrees of toughness as compared to the engineering steels, are encountered. The tensile transverse bending, and impact tests have limited usefulness when applied to hardened tool steels as results are apt to vary and the average is only approximate. The static torsion test has the advantage over the above in that the applied stress is not so much concentrated

and it is possible to measure much more accurately both strength and toughness even when the latter is very low. With this method of testing, simultaneous observations of both stress and strain are made, and from these results curves can be plotted showing both the elastic and plastic deformation and the approximate location of the yield point.



Fig. 44

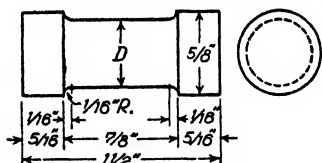


Fig. 43 and 44—Compression test specimens for tool steel. With both specimens trim "D" to about 0.020 in. oversize. After hardening grind "D" to 0.505 ± 0.0005 in. Grind both ends square and parallel with no centers. Use special care in finishing the radii in Fig. 44.

The angle through which the specimen twists is recorded for each increment of 25 in. lb. torque until rupture occurs. From these data a stress-strain curve can be plotted which gives information as to the elasticity, plasticity, and ultimate torsional strength of the material being tested.

XIV—Cutting Tests—See the work of F. W. Taylor, "On the Art of Cutting Metals," Trans., A.S.M.E., 1907, v. 28.

XV—Fatigue Testing of Tool Steel—The ordinary fatigue tests used on soft or medium hard materials may be, but seldom are, applied to annealed tool steels, since tool steels are largely used only in the hardened condition. These tests are not generally used on hardened tool steels because the variations in results due to notches, scratches, and residual strains overshadow those caused by differences in steel quality. Their best application on tool steels would be on specimens that have been hardened and then tempered to comparative softness—a treatment seldom used for tools.

Fatigue tests of tool steel indicate an endurance limit of from $\frac{1}{4}$ to $\frac{3}{4}$ of the static tensile strength, and show that the fatigue resistance is materially increased by changing the direction of final polish of specimen from circumferential to longitudinal.

The main emphasis in dealing with fatigue problems in tool steels should be laid on the design and treatment.

Some manufacturers and users of hollow mining drill steel have long used a practical fatigue test to check the quality of various lots of this material. This test with modifications may be applied to other types of pneumatic tools. It consists of running a representative number of test bars of definite size and length in a jack hammer until failure occurs from fatigue. The time required is compared with standards agreed upon by manufacturer and consumer.

XVI—Damping Capacity—Damping capacity is that property of engineering materials and particularly of metals which enables them to dissipate energy without failure when subjected to cyclic stresses below the fatigue limit. This property is also known as "mechanical hysteresis effect," "dynamic ductility," and "internal friction" of solids. The damping capacity of a material is the amount of work dissipated into heat by a unit volume of the material during a completely reversed cycle of unit stress, and is measured in in.lb. per cu.in. per cycle. To study this ability of metals to dissipate energy when stressed well below the elastic limit by the method of measuring the areas of "hysteresis" loops demands extremely delicate apparatus and test methods. The method generally employed is that of measuring

Method of Making Torsion Test—Owing to the high strength and low toughness of hardened tool steels, a test specimen with a comparatively high ratio of "L" to "D" is necessary for best results; (L = length of gage section, D = outside diameter of gage section). Where a ratio of 5.78 is used for relatively soft materials, a ratio of 16 is recommended for hardened tool steels so that sufficiently large strain values can be obtained for a given stress. A drawing of the torsion test specimen for tool steels, picture of the torsion testing apparatus, and details regarding the method are given on pages 47 and 49, A.S.T.M., Proc., 1931, v. 31, pt. 2.

The principle of the test is that by means of a manually operated turning head, a twisting torque is applied to the torsion specimen which in turn transmits the torque through a lever system and hydraulic gage to a piston. The gage reading indicates the applied twisting force or torque in in. lb., and deformation or angle of twist is directly measured on the twisting head of the machine.

the cumulative effect of such hysteresis loops by observing the rate of damping out of vibrations in specimens of the metal. A simplified type of apparatus is shown in Fig. 46.

A specimen S , usually round and solid, is twisted slightly by the action of two magnets M_1 and M_2 . When the current in the magnets is broken, the specimen vibrates back and forth and a record of its vibrations is made on a paper P , which is moved by clockwork. An ideal "damping" machine would be one which permitted damping of a freely vibrating specimen only by internal friction in the specimen.

Although it seems proper to co-ordinate higher damping capacity with smaller tensile or hardness values, at least so far as steels are concerned, many experiments have shown that the damping capacity may be quite different for steels of identical chemical and tensile properties. A material of high damping capacity is less sensitive to the influence of surface notches or sudden changes in cross section than one of lower damping capacity.

Duralumin has an extremely small damping value; on the other hand, cast iron has a surprisingly high damping capacity.

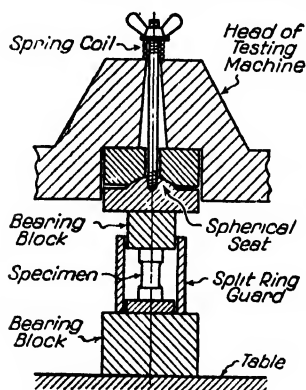


Fig. 45

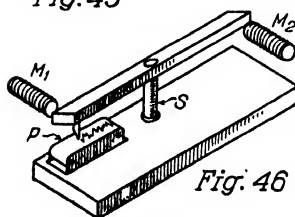


Fig. 46

Fig. 45—Method of making compression test. Fig. 46—Apparatus for damping test.

XVII—Magnetic Testing—See page 770 for an article on Magnetic Testing.

XVIII—X-Ray Test—Radiography—Defects occurring in tool steels are usually of such a nature that they are not readily revealed by the X-ray.

Diffraction Methods—Diffraction or crystal structure analysis has been used for fundamental studies of the components of tool steels but no routine inspection has been established.

XIX—Determination of Critical Points—There are three methods of determining critical points of tool steels: (1) One is by plotting the heating and cooling

curves on time-temperature co-ordinates (Fig. 47); or (2) by dilatometric measurements involving the charting of interruption of progressive expansion or contraction on linear expansion temperature coordinates; or (3) by plotting the change or loss of ferromagnetic characteristics on a temperature magnetic intensity diagram.

1. Thermal Critical Point—In ordinary practice, critical points are critical ranges, since a small temperature range is required to complete the change in physical and physicochemical characteristics.

The method of inserting a thermocouple into the drilled test sample and observing and recording the rate of rise or rate of drop of temperature on time-temperature diagram is probably the oldest and most simple method of obtaining the critical points.

A heating and cooling rate of from 1-2°F. per min. is used to determine with fair accuracy, the transformation points. Its accuracy, of course, depends largely upon the quality of furnace equipment. To eliminate this factor, a neutral or nontransforming metal such as platinum, austenitic nickel steel, or austenitic alloy steel is heated along with the sample and temperature differences of the two observed. The inverse rate of heating and cooling curves, shown in Fig. 47, give sharp peaks on the curves which correspond to the amount of heat absorbed on heating or the heat evolved on cooling. The inverse rate curves are in general use. Autographic recorders are very desirable and where frequent determinations are required, they are indispensable.

Dilatometric Method—The dilatometer is essentially a mechanism for determining the expansion or contraction of a sample with changes in temperature.

Magnetic Method—The magnetic determination of critical points depends upon the loss of ferromagnetic properties and by observing the magnetic transformation and the corresponding temperature these points are established. The tool steel sample is inserted as an armature in a magnetic circuit and when the tempera-

ture is reached at which magnetic flux ceases to pass through the steel sample or when it disrupts the circuit, the loss of ferromagnetism indicates the critical point. A galvanometer connected into the line will drop to zero position and may be made to record this loss on the temperature curve.

XX—Abrasion Tests—Abrasion testing consists of measuring the loss of weight of the unit surface area of a sample of tool steel, after moving over and in contact with a standard hardened and finished machined surface, for a definite number of strokes and under a definite pressure, representing, as far as practical, service conditions.

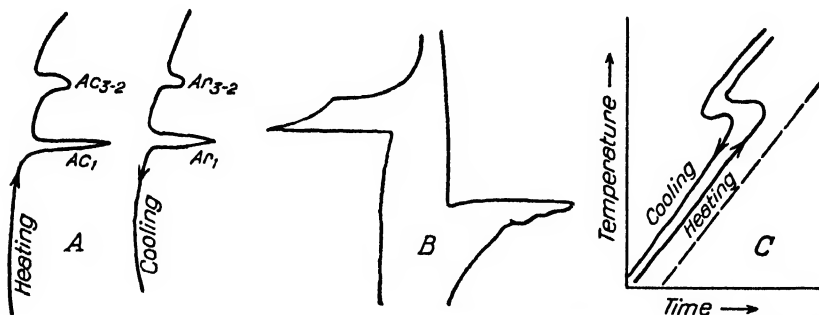


Fig. 47—Different types of critical point curves. "A" inverse rate heating and cooling curve for a 0.45% carbon steel, and "B" the same for a 1.00% carbon steel. "C" smear expansion of a 0.45% carbon steel as determined on a dilatometer.

This loss per unit area of the tool steel sample compared with the loss per unit area of other samples of different physicochemical composition, but of identical surface dimensions and tested in this same manner, gives the abrasion value expressed in loss of weight units per unit surface.

The surfaces may be cylindrical, spherical, or flat, but whether they are curved or straight, maximum and uniform contact and proper machine or mechanical finishes are essential.

See the A.S.T. Trans., v. 10, p. 692, French and Herschman, Wear of Steel, with Particular Reference to Plug Gages, for illustration of wear testing machine for cylindrical surfaces.

Acknowledgments—The Subcommittee on Tool Steel wishes to acknowledge and thank the following individuals for the valuable assistance which they gave the committee in the preparation of this report: Oscar Harder, Henry Keshian, Kent R. Van Horn, Vincent Malcolm, F. H. Allison, Jr., C. W. Schuck, O. W. Boston, R. L. Templin, B. H. DeLong, J. V. Emmons, H. F. Moore, H. T. Morton, and R. G. Kennedy, Jr.

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Notched Bar Testing of Steel*

Good practice in the design and manufacture of steel parts avoids, wherever feasible, the occurrence of notches and sharp changes in cross section, while sound metallurgical practice seeks likewise to avoid the presence of coarse slag inclusions, internal cracks, and other defects which are likely to simulate external notches. The action of such notches is to concentrate the stresses resulting from applied loads, and when the notch is sufficiently sharp, a crack is produced, the propagation of which causes failure of the part. These failures are of the brittle type, characterized by complete cleavage through the notch, though the metal may be ductile when not subjected to the stress conditions of a notch. Steel parts differ in their susceptibility to a notch effect and this difference is frequently not indicated by any of the tests carried out on unnotched specimens. This article discusses notch behavior and gives a test procedure for use with steel.

Because the conditions encountered in service are frequently complex, and the precise state of stress unknown, it is not to be expected that it will always be possible to correlate service failures which are due to a notch or to notch brittleness, with tests on notched bars carried out in the laboratory. However, by recognizing the principles of notch behavior, it should be possible to establish a notched bar test that will serve as a guide to the selection of a metal (and its treatment) of sufficiently low notch sensitivity when that is required. It must be borne in mind that it has not been demonstrated that there is any connection between notch sensitivity as measured in a test involving a continuous application of load and notch sensitivity as measured in tests in which the load pulsates as in notch fatigue testing. The broad principle upon which a notched bar test should be planned and interpreted is as follows: All steels break in the brittle manner under a notch of sufficient severity, but the severity of the notch required to cause brittle failure may vary somewhat among steels which have the required strength and ductility and it must be independently determined; furthermore in this test steels may also vary in the temperature below which failure will be brittle for a notch of a particular degree of severity.

Distinction Between Notched Bar Testing and Impact Testing—The notched bar test distinguishes between conditions of steel which are more or less sensitive to a notch while an impact test distinguishes between conditions of steel which are more or less sensitive to the speed at which the metal is deformed. Notch sensitivity and velocity sensitivity are two different and distinguishable characteristics and should be studied by different test techniques. Due largely to the circumstance that the energy to fracture the notched test bar is determined on an impact machine, the test is commonly called an "impact" test and considerable misunderstanding has arisen as to its correct nature. More often than not, it is regarded as a test of behavior under impact and hence it seems desirable here to point out that the stress conditions imposed by a notch and the stress conditions imposed by an impact belong in entirely different categories. Notch sensitivity of a steel can be detected and studied by methods which use purely static loading. A bad effect of this misunderstanding is that the attempt is improperly made to correlate the energy absorption of the notched bar test (the impact value) with behavior in service which involves merely impact or "shock" with no notch present. The true correlation is with service behavior which involves the stress conditions of the notch effect. In some cases, which are not well understood at present, it is recognized that a notch brittle condition is observed in impact or at one speed of loading but not at a lower velocity. Obviously these are cases of "velocity sensitivity" and they ought not be overlooked in practice.

Theory of the Notched Bar Test—The Ludwik theory of the notch effect¹ shows that brittle failure of ductile steel is produced when the cohesive strength is exceeded before deformation sets in. The cohesive strength is defined as the strength property of the metal that resists the tensile, disruptive stress across a plane at right angles to the applied load. In the tensile test the steel is ductile because the elastic limit in shear is low enough to permit flow by slip before the cohesive strength is exceeded. As long as the cohesive strength is at least at this level with respect to the elastic limit in shear there is nothing in the tensile test to indicate whether it is high or low, relative to the cohesive strength and shear yield that is usually expected for

*Prepared by the Subcommittee on Notched Bar Testing. The membership of the subcommittee was as follows: S. L. Hoyt, Chairman; E. C. Bain, M. Gensamer, G. C. Riegel, R. Sergeson, and G. H. Wright.

that steel. The presence of a notch alters the relation between the normal stresses, which tend to part the metal by brittle fracture at 90° to the direction of the stress, and the shear stresses, which tend to make the metal deform by slip along planes at 45° . As a result of a large number of studies of the effect of a notch on the stress conditions it is known that the ratio of normal stress to shear stress is greatly increased. There is also a marked concentration of the normal stress at the root of the notch which is particularly pronounced when a bending moment is applied. In this way the normal stress may rise above the cohesive strength and produce a brittle fracture before the shear component is high enough to produce plastic deformation.

In notched bar testing we are usually concerned with the notch toughness of a steel which meets certain requirements for strength and ductility in the tensile test.

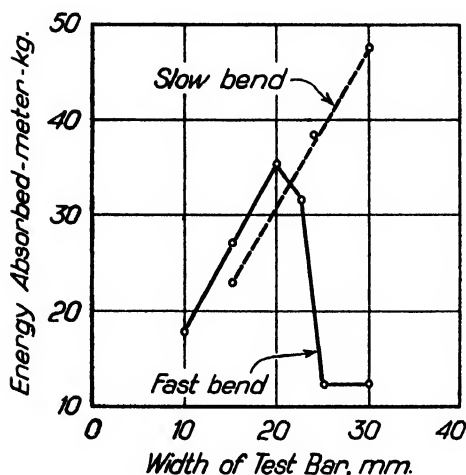


Fig. 1

Fig. 1—Effect of width of bar on the impact value. Height of all bars was 30 mm. (Moser).

Here the resistance to plastic deformation is fixed at the level of the yield point, converted into the shear stress at 45° to the axis. The cohesive strength is not determined directly but an idea of its level can be obtained if we know the intensity of the notch effect required to produce brittle failure. The principle is illustrated by Fig. 1 taken from the work of Moser.² As the width of the test bar is increased, with the notch remaining the same in all bars, the intensity of the notch effect increases. In the case of the steel specimens used in the illustration a width of 2.5 cm. was required to produce brittle fracture. Other steels of the same tensile properties might require a narrower or a wider bar for brittle fracture and they would be less or more notch tough respectively than the steel represented.

Cohesive failure with little deformation requires but little energy and hence in the notched bar test a small impact value is recorded for notch brittle steels. The Ludwik theory makes it clear that the ordinary tensile test,

or even an impact test on a plain bar, cannot be used as a substitute test for notch sensitivity.

Present Testing Practice—At present a "standard" notched bar is broken by a single blow on a pendulum type impact machine, at the ordinary laboratory temperature or at some specified temperature, and the energy required to break the bar is determined in foot pounds. This impact value is used as a determination of the "notch toughness" of the material, though good practice requires this to be judged according to what has been proven to be acceptable or not acceptable for the material in question, and its application. It may be pointed out here that a single test shows only that the specimen broke in a tough or in a brittle manner when tested under the specific test conditions used, but does not reveal what the behavior would have been had other test conditions been used. These points will be dealt with again under the proposed procedure.

Impact Testing Machine—Two types of impact machines are commonly used, the Charpy and the Izod, both of which employ the swinging pendulum. Instrument manufacturers have modified certain details of these machines, but the principles of all will be made sufficiently clear from the following description. Either type of notched bar can be used with either machine, though, as will be made clear directly, the length of the bar and position of the notch are different for these two machines. The Charpy machine has a total available striking energy of 30 meter-kilograms (217 ft. lb.). The bar is supported at both ends as it lies in position on the split anvil and is broken by a blow opposite the notch. The distance between supports is 40 mm. or 1.575 in. The Izod machine breaks the bar by a blow at the end as the bar is held rigidly in a vise. The notch comes just outside the jaws. In both

cases the test bar is broken by a single blow and after breaking the bar, the pendulum swings past the anvil and rises to a height which depends on the amount of energy which was extracted by breaking the bar. In other words the work which is done in breaking the test bar takes that amount of energy out of the moving pendulum with the result that it does not rise to the height it would if swinging freely. Hence the energy to break the bar is given by the effective weight of the pendulum times the height of fall minus the height of rise, with a small correction for friction and windage. A scale with moving pointer gives the reading of the "impact value." This may be either in foot pounds direct, or in the angle of rise which is converted into foot pounds. At times only one bar is broken though it is better to use two or more to secure a check.

The Charpy test is commonly used in continental Europe, and the Izod test is used in England. Although this country has not attempted to select a standard notched bar test, and both the machines and both of the notches are used, the advantages of the Charpy notch and the absence of a vise for holding the specimen make the Charpy test appear preferable for a standard. On the other hand the Izod may be better suited to testing rounds and miscellaneous shapes.

Type of Specimen*—In this country two test bars are used, one the Charpy bar of Fig. 2 and the other the Izod bar of Fig. 3. The Charpy bar should be either 2 in. long or 2.165 in. long, depending on the testing machine. The main difference between these bars is in the notch. The Charpy notch is of the key hole type with a radius of 1 mm. (.0394 in.) and a depth of 5 mm. (.197 in.). The Izod notch is also used for test bars which are broken on the Charpy machine. A record of the impact values of notched bars should be accompanied by a statement covering the notch which was used. On account of the difference in the design and depth of the notch, test results with these two bars cannot be directly related though it is possible to secure a calibration of one in terms of the other. In general if a specimen is tough, the Izod value will be above the Charpy value because a greater cross section is broken, while if the steel is critically notch brittle the Izod value will be lower because the V notch gives a more severe notch effect.

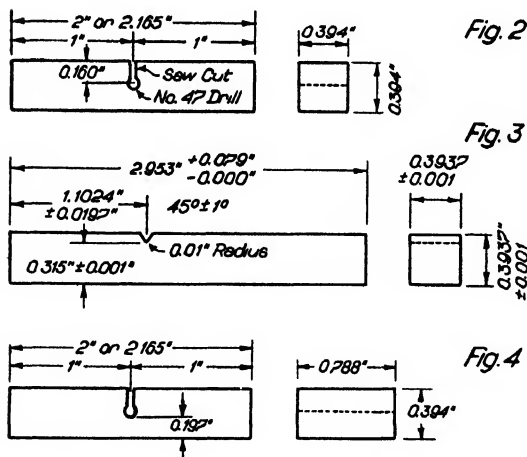


Fig. 2—Charpy notched impact specimen.

Fig. 3—Izod notched impact specimen.

Fig. 4—Proposed test bar of intensified notch effect which is the same as Fig. 2 except for double the width.

ing, or grinding but care should be exercised to avoid enlarging the hole or cutting into the side of the drilled hole. The latter can be avoided by placing a copper wire in the hole while making the saw cut. Test bars which are to be broken in a hardened condition require a special technique. The hole cannot be drilled but, with

The notch of Fig. 2 is preferred by many on account of the ease of making it and particularly on account of the precision with which it can be reproduced. The hole is drilled with a No. 47 drill which, with a diameter of 0.0785 in., is close to the Charpy standard of 2 mm. or 0.0788 in. By placing the bar in a fixture this hole can be drilled tangent to the center line so that the depth of section to be broken can be held to just 5 mm. or 0.197 in. The drilling operation leaves the scratches running around the hole, or in the most favorable direction to avoid low results arising from them. For greater reproducibility the hole can be carefully reamed out but that is seldom considered necessary. If the steel is too hard for drilling (about 400 Brinell or 40 Rockwell C hardness numbers) the notch can be made by grinding. After the hole is drilled, a slot is opened up to the surface by sawing, mill-

*Attention is directed to the A.S.T.M. specification of a sharp V notch for the test bar which is broken on the Charpy machine, as is given on page 135.

suitable precautions, can be ground to dimension. It is also feasible to drill the hole before hardening and to insert a soft steel wire which will completely fill out the hole, and then to heat treat the test bar. This hole is subsequently opened up to the surface.

The Izod notch is used by some because it gives a larger numerical spread between notch tough and notch brittle materials than is obtained with the more generous radius of the Charpy notch. On the other hand the radius of the Izod notch is so sharp that reproducibility is sacrificed unless great care is exercised in its production. Furthermore, the Izod notch is so shallow that the volume of deformed metal may extend out to the outer face of the test bar. When this occurs, the full notch effect is not developed and the use of the impact value as a measure of the notch toughness is vitiated.

Precautions Necessary for Reproducibility of Results—Two features of great importance are the method of making the notch, and placing the bottom of the notch tangent to the center line of the bar. The other dimensions should be held as shown. The accuracy which is usually maintained is ± 0.001 in. though if it will lower the cost of preparing test bars this can be increased to ± 0.003 in. on harder steels and to ± 0.005 in. on softer steels without endangering the reliability of the results. The jig which is used in drilling the hole may require the more accurate finish.

The impact machine should be known to conform to standard requirements, and to be of correct calibration. Frictional losses can be checked from time to time by permitting the pendulum to fall freely and noting the decrease in the oscillations. The small fixture which is used to place the test bar at the correct position on the anvil can also be used to check the zero position of the pendulum. The test bar should be accurately placed on the anvil so that the tip of the pendulum will strike it at a point opposite the notch. This placement can be properly made with the aid of a template. Furthermore, the anvil should be so designed that the test bar clears the sides of the anvil with no undue loss of energy from scraping.

The effect of variation of temperature in notched bar testing is extraordinarily great. The laboratory temperature may vary as much as 30°F . between summer and winter and with some steels this is sufficient to affect the impact values materially. To obtain reproducible results in some cases requires holding the temperature of the test bar to a range which does not exceed 10°F . The effect of temperature will be commented on at greater length in a later section.

Other factors which affect the consistency of the results are associated with taking the sample and conditions of heat treatment. Forgings and rolled sections have definite flow lines or fibre, while nonmetallic inclusions are also drawn out in directions parallel to the direction of metal flow. If the length of the test bar is parallel to the direction of the fibre the impact value is higher, at times by as much as twofold, than it is if perpendicular to that direction. Furthermore, the direction of the notch in the test bar may likewise have an effect on the impact value. Heat treatment frequently alters the surface. Usually this change is a decarburization, which usually acts to increase the impact value, though it may be a carburization which acts to lower the impact value. The discussion of such factors could be elaborated, but it is sufficient to say that in each case the test bar should be made by a procedure which insures having the metal in the desired condition. As a precautionary measure, at least 0.025 in. can be left on all faces for final machining and grinding, and the notch can be made last.

Inasmuch as most notched bar testing is done on impact machines, the velocities of which do not vary materially, the effect of velocity on the reproducibility of the results is not often significant. Considerable work has shown that with most steels, about the same energy absorption is secured whether the bar is broken statically, or by impact at normal speed. On the other hand it has also been shown that some steels are velocity sensitive and when broken statically they remain tough in wider sections or with sharper notches and at lower temperatures than when broken by an impact. This field of velocity sensitivity requires more study than has been put on it before an adequate discussion can be given.

Proposed Procedure for Notched Bar Testing—Present practice is correct for determining the impact value of a specimen under the specified conditions of the test used but is not capable of giving a complete understanding of the notch behavior or notch toughness of that steel even for a single condition of treatment. In brief when we test a steel with a specific notch, at normal laboratory temperature, and at the speed of a standard testing machine, we learn whether or not those condi-

tions are severe enough to develop brittle behavior in the specimens tested. If we know that the notch used is just sufficiently severe for the particular application to be made, the test is adequate. This is particularly true in view of the improvement in the uniformity of steel making and steel treating practice of recent years. On the other hand, the conditions of service may be of such a nature that the standard test no longer suffices; the notch used may be too severe or not sufficiently severe. This must be ascertained by experience. The following is given as a guide to correct laboratory procedure, when the application involves notches more severe than that of the standard test or when a more searching test is desired. This involves the use of variables which alter the notch effect of the notch used, the temperature of the test bar, and the striking velocity.

It has been shown that a notch of a given sharpness and depth has a greater effect on the ratio of the maximum normal stress to the maximum shear stress, if the width of the bar is increased. The proposed test bar of intensified notch effect is shown in Fig. 4 which is double the standard width but otherwise the same as the standard bar. The energy required to fracture is obtained as before and compared with the value for the standard bar. The selection of this width is arbitrary but experience has shown that it is satisfactory. Breaking the double width bar gives valuable information on the quality of the steel. Ordinarily it gives about double the single width value but may fall well below this and even below the value of the standard bar. Depending on the single and double width values, the steel is accepted or rejected, or diverted from the use originally intended to one which is less critical. In about the same way bars of triple width may be broken and the impact values compared with those of the single and double width bars. The desirability, or necessity, of so extending the test is to be determined for the individual application. Somewhat the same judgment could be secured by comparing the Charpy notch with the sharper Izod notch. If the steel is sufficiently notch tough, the greater area of the Izod bar will give greater impact values; but if the steel is notch sensitive, its more intense notch effect will give a lower impact value. The double width bar is more convenient, for use can be made of the simple mathematical relationship between the double width value and twice the single width value to judge the steel. Single and double width bars with the Izod notch (or other V notch) can also be used in special cases.

A second condition that requires an extension or modification of the standard test is that imposed by service temperatures which lie below the ordinary laboratory temperature. The strength and ductility of steel in the tension and torsion tests vary but little over the range of atmospheric temperatures. A test for those properties can rationally be made at room temperature though the operating temperature be lower. Notched behavior comes in quite a different category. A steel which is relatively insensitive to a certain notch at room temperature can be quite notch brittle at a lower temperature. In many cases this change in behavior can be brought about by lowering the temperature to the freezing point (32°F.). If a different notch is used, the temperature at which notch brittle behavior is produced will be higher as the severity of the notch effect increases. Obviously it may be necessary on some occasions and desirable on others to test steel at some temperature below room temperature. Such a procedure has already been incorporated into testing inasmuch as acceptance of steels for low temperature service is based on notched bar tests at temperatures ranging from -58°F. down. It is proposed that this factor be more fully taken into account and that test temperatures be utilized, when the occasion warrants, which lie below room temperature. This amounts to a recognition of the rapid change in notch toughness that can occur over this particular temperature range.

When carrying out subnormal tests the test bars should be held at the temperature in question for at least 30 min. or until equalized, and then broken quickly. These temperatures can be readily enough obtained in the laboratory by using tap water, chilled water, melting ice, and freezing mixtures. In the case of temperatures which lie well below normal, the test temperature is secured by means of dry ice plus acetone, or even with liquid air.

"Velocity sensitivity" of steel when tested by a notched bar test has already been mentioned. A complete procedure should include a test of this factor whenever it is an important component of the service conditions. A promising method of attack is that of determining the static stress-strain diagram of the notched bar and comparing the energy value with the impact value as ordinarily determined. The static diagram further characterizes the steel by distinguishing between strong steels and ductile steels, both of which may have the same impact value. It may

also be used to determine the amount of energy absorbed up to the point of failure by crack formation. That value appears to be a more significant criterion than the total energy of rupture.

Interpretation of Test Results—The interpretation of notched bar test results necessarily involves certain strict limitations. First of all the test is pertinent only to such applications as involve the effect of notches to reduce the manifestation of plasticity in the material. At times it will be employed to verify the degree of the sensitivity of a steel composition or of a heat of steel to the notch effect, or to ascertain the effect of a thermal or a mechanical treatment. In any comparison of this kind the specimens of the material in question must be comparable in the other essential characteristics with those specimens which serve as a criterion. Thus, for example, they should, depending upon use, have the same ultimate strength or the same yield strength or the same tensile ductility or the same hardness (a difference in the tempering temperature which would make even two or three points difference in Rockwell C hardness may greatly alter the results of the notched bar test even in specimens from the same bar).

Furthermore the grain size established in the material in question should not be coarsened by an unsuitable heating temperature in hardening for this alters the notch response of any steel tremendously. Internal stress is particularly potent in determining notch sensitivity of a specimen and care should be taken, in quenching and tempering technique, for example, not to vitiate the comparison by a disparity in this respect which in good commercial practice would not exist.

Table I

The proportional limits, yield points, tensile strengths, fatigue strengths, and notch fatigue strengths are in psi. The elongations and reductions in area are in per cent. S.W. = single width bar, and D.W. = double width bar.

Item	C	Mn	Ni	Cr	Pr. Limit	Yield Point	Tensile Strength	Elong. in 2 in.	Reduction in Area	Charpy Values— S.W. Ft. Lb. D.W. Ft. Lb.
1 ^a (Forging)	0.55	0.71	...	...	65,000	68,700	108,800	25.0	54.0	14.8 27.8
2 ^b (Forging)	0.65	0.58	...	...	62,000	66,000	112,900	23.0	44.0	8.5 6.1
3 (Forging Norm. and tempered)	0.40	...	...	...	62,000	63,500	100,000	25.0	58.8	11 6 15 6 15 6
4 (Forging—Oil Quench and tempered)	0.40	...	...	...	74,000	82,000	128,000	17.0	45.0	15 31 15 27 14 30
5 (Forging—Treatment Unknown)	0.45	0.56	...	...	55,000	.....	91,400	28.5	61.8	19.5 8
6 (Forging—Oil Quench and tempered)	0.45	0.56	...	...	58,000	.....	96,000	26.5	60.0	19.0 37
7 (Forging)	0.45	0.55	3.20	1.12	98,000	101,500	128,700	23.0	56.0	7 13
8 (Forging)	0.45	0.55	3.20	1.12	101,000	107,800	133,000	20.0	50.0	30 67

^aFatigue strength 45,000; notch fatigue strength 21,000.

^bFatigue strength 35,000; notch fatigue strength 23,000.

Item	S.A.E.	Tempering Temp., °F.	Rock. C	Yield Point	Tensile Strength	Elong., 2 In.	Red. Area	Charpy, Ft. Lb.
9	1045	600	47-49	120,000-135,000	175,000-195,000	8.5-12.5	30-45	4.5-7.5
10	1045	800	38-40	100,000-115,000	145,000-160,000	12.0-14.0	42-48	18-24
11	2345	425	51-53	220,000-230,000	285,000-305,000	11.0-14.0	34-42	16-20
12	2345	500	48-51	225,000-235,000	260,000-275,000	9.0-13.0	36-45	16-15
13	9260	980	42-44	155,000-165,000	195,000-205,000	11.5-13.5	25-33	11-14

Comments on Table I

Items 1 and 2 give a comparison of two steels of closely similar tensile properties.

Item 2 is deficient in impact value, particularly at double width.

Items 3 and 4 compare two carbon steel forgings of different heat treatment. Item 3 is seen to be deficient in the double width impact value though it is otherwise of good properties.

Items 5 and 6 illustrate the effect of heat treatment on a carbon steel forging. The double width bar brings out the better condition of Item 6.

Items 7 and 8 show two different conditions of a forging, with satisfactory and unsatisfactory impact values.

Items 9, 10, 11, 12 and 13 give typical properties of several S.A.E. steels. Items 9 and 10 represent $\frac{1}{2}$ in. round bars water quenched and tempered as shown. Items 11 and 12 represent .520 in. round bars oil quenched and tempered as shown.

It will be clear from what has been said that the simple test may be quite inadequate. This situation places great emphasis on the test conditions which are used in notched bar testing. It also reflects the technological nature of this test, for it does not measure a property but simply reveals the behavior of the steel under certain specific conditions.

While this article deals with testing procedure rather than with test results it may clarify matters by citing an illustrative case. A medium carbon steel forging was given two different heat treatments and tested after each one. In both cases the standard Charpy bar with key hole notch gave 15 ft-lb. Undoubtedly either heat treatment would be suitable for many applications. The testing procedure which is advocated here showed one of them to be inadequate for more exacting service. When the double width bars were also broken it was learned that with one heat treatment a value of 30 ft-lb. was obtained, and with the other only 7 ft-lb. Incidentally, the steel in the latter condition was found to be softer and more ductile in the tensile test. For more exacting service, or if a good factor of safety is desired, it is clear that the steel cannot be judged adequately on the basis of the standard test alone. On the other hand, if only double width bars are used, some material may be rejected though it be suitable for less severe service.

As a guide to normal impact values which may be expected for a number of typical cases the data of Table I are given.

References

¹P. Ludwik, Was Haben Wir an der Kerbschlagprobe? *Stahl u Eisen*, 1923, v. 43, p. 1427; Über die Bedeutung der Elastizitätsgrenze, Bruchdehnung und Kerbzähigkeit für den Konstrukteur; *Z. Metallkunde*, 1924, v. 16, p. 207; Die Bedeutung des Gleit- und Reiss-Widerstandes für die Werkstoffprüfung, *Z. Ver. deut. Ing.*, 1927, v. 71, p. 1532.

²M. Moser, A New Method of Interpreting Notched Bar Impact Test Results, *Trans., A.S.S.T.*, 1925, v. 7, p. 297.

Inspecting and Testing of Bolts, Screws, Nuts, Studs, and Pins*

General—The inspecting and testing of parts having threaded sections such as bolts and screws may include one or more of the tests covered in this article, which are as follows:

Chemical Analysis	Elongation
Mechanical Inspection (Dimensions)	Reduction of Area
Inspection of Finish and Appearance	Head Test
Hardness	Bend Test
1. Brinell	Shank Fracture Test
2. Rockwell	Impact Test
3. Scleroscope	Torsion Test
4. File	Shear Test
Tensile Test	Thread Stripping Test
Elastic Limit	Macrostructure
Yield Point	Microstructure
	Inspection of Coatings

Appearance and Finish—These products should be free from harmful defects such as burrs, laps, excessive scale, rough tool marks, dirty threads, rust, and visible raw material defects. The application to be made of any item usually determines what may be considered as harmful.

Sampling—When a shipment is made up of a number of containers such as kegs or boxes it is suggested that, for testing, one or more samples should be taken from each container, thus representing as nearly as possible the average quality of the shipment.

Mechanical Inspection—The physical dimensions are determined by suitable rules, gages, micrometers, and special instruments. Thread dimensions and tolerances for the several classes of threaded products are specified in the report of the National Screw Thread Commission and are accepted as standard.

An essential part of mechanical inspection is the frequent checking of the routine testing instruments against master gages.

Chemical Analysis—The important elements are determined by the well established methods for chemical analysis and from representative samples taken from the entire cross section of the part.

Hardness Determinations

Brinell Hardness Testing—The Brinell hardness test is generally used when the size, shape, and character of the section permit. When possible, the Brinell hardness determination on headed sections should be made near the center on the top of the head. The sample pieces may be slightly but smoothly ground when it is necessary to remove scale, decarburization, or surface roughness. See the article on Brinell Hardness in this Handbook for details of preparing the specimen and making the test.

Scleroscope Hardness Testing—The Scleroscope test may be used where the indentation resulting from the Brinell or Rockwell test would be objectionable because of impaired surface finish or serviceability. See article in this Handbook for details on the method.

Rockwell Hardness—The Rockwell C scale is used on hard surfaces and the B scale on soft surfaces where size, shape, or application of materials will not permit the use of the Brinell. See the Rockwell Hardness article in this Handbook for details of the method.

Monotron—For case hardened parts the monotron may be used. For details see the article in this Handbook on this method of testing.

File Hardness—Although its use is not standardized, the file is often used as a guide in estimating the hardness and uniformity of surface hardened parts, especially where resistance to abrasion is of major importance.

Tensile Tests—A threaded section may be considered as a cylinder strengthened by one or more spiral ridges which are the threads of the screw.

*This article was prepared by the Subcommittee on Bolts, Screws, and Nuts. The membership of the subcommittee was as follows: H. B. Pulsifer, Chairman; C. L. Harvey, and C. E. Zwahl.

The strengthening effect of the threads is usually greater on the yield point and elastic limit than on the tensile strength and is usually greater for coarse than for fine threads.

An excellent method for writing specifications is to state the minimum load in pounds for the yield point or tensile strength that a given specific part should sustain. This must be appreciably lower than the expected mean loads because of the distribution of results (see section headed *Distribution of Results*).

With bolts that are roll threaded but not heat treated the strengthening effect is greater than for either fine or coarse cut threads. The greatest strengthening effect is after a cold extrusion of the size of the pieces in the section to be threaded followed by roll threading. Materials that harden rapidly on cold working (stainless irons) also have large increases in strength after roll threading. In the extreme case, the strengthening effect of the threads may be the equivalent to an area increase of the full cross section of the piece.

It is recommended that the mean diameter¹ be used as the basis for calculating the area of threaded sections. This is done in spite of the fact that the area based on root diameter is in common practice at the present time.

The tensile properties of unthreaded sections are calculated on the minimum cross sectional area. If when testing a threaded section, the part breaks outside of the threaded section, the area of the section that breaks should be used for the calculation.

Tensile tests should always be made in special self-aligning grips. On threaded sections, tension is applied between the head and a nut screwed onto the threaded end, or special split threaded grips. Since a straight section turned out of a threaded piece may give a result far from the properties of the piece when pulled as a threaded section, it is recommended that the actual piece should be tested whenever possible.

True Elastic Limit—The elastic limit is determined in the tensile machine and is denoted by the number of pounds required to produce permanent deformation, which is determined by dividers, extensometers, or by means of an autographic attachment. The value is expressed in terms of pounds per square inch. On the threaded sections, the value is figured on the mean area.

Yield Point—The yield point is usually determined by the "drop of the beam" on the screw type machine or by the action of the pointer on the hydraulic machine.

Tensile Strength—The tensile strength, determined in the tensile machine, is the maximum load in pounds required to break the specimen and is expressed in pounds per square inch, figured on the mean area.

Elongation—The elongation of a threaded section is measured after the tensile test and is usually expressed as the percentage increase in length of a measured section (usually 2 in.). If the entire elongation is in a short length (less than 2 in.) of the threads, it is only necessary to divide the total elongation, expressed in fractions of an inch, by 2, to get the percentage elongation in 2 in.

Reduction of Area—The reduction of area is seldom determined on threaded sections. This determination is desirable, however, when testing a standard test specimen because the reduction of area and the elongation are indicative of the toughness and ductility of the metal.

Head Test—To determine if there is proper union between the head and shank, samples may be tested by placing the bolt sideways on a block of steel with its head just over and against the square edge. The head is then hammered vigorously to determine if the steel deforms plastically or ruptures.

Bend Test—Although it is not standardized, the bend test is often used on the shank of bolts as an aid in judging the toughness and ductility.

The bend test is best made in the tensile machine with a specially designed fixture which contains a series of mandrels of various sizes, thus permitting the bolt to be bent on a mandrel, the rounded end of which has a radius the same as that of the bolt.

Shank Fracture Test—The shank of these products may be fractured to show

¹The mean diameter is considered the mean between the root and pitch diameters.

visible defects such as piped steel, seams, or coarse crystallization. These defects will probably be visible to the naked eye or through a hand lens.

Impact Test—There are three classes of impact testing machines: (1) Drop weight; (2) pendulum; and (3) flywheel. These machines differ according to the method used to energize the moving mass. With each of the above classes of impact testing machines, there may be used four types of impact specimens, depending upon the way in which they are ruptured and the way they are held on the anvil: (1) Tension, (2) shear, (3) simple beam, and (4) cantilever.

Bolts, screws, and nuts are usually subjected to tensile impact service, but regardless of type, all impact testing should duplicate actual service conditions as far as possible, especially in method of supporting specimen, application of stress, and tightness of the nuts.

A common qualitative test to determine the core toughness of surface hardened parts is to subject the piece to hammer blows.

Ordinary steels increase rapidly in brittleness as the temperature is lowered to or below freezing. Accordingly, they should not be tested at a lower temperature than the one at which they are expected to show freedom from brittleness.

Torsion Tests—When it is necessary to test the torsional strength of these products, it is recommended that it be done so that the actual foot pounds can be measured. The test should be made on a torsion machine.

Shear Tests—Shear tests are best made in a special shear block in which holes in the block and plunger hold the specimen rigidly in alignment. The holes must be close fitting and the block and plunger of hardened steel. The block is used in the tensile machine.

Thread Stripping Test—The strip test for threads is applied to threaded sections, including nuts, and when possible it should be made in tension on assembled units.

Macrostructure—To determine the character of grain flow (in headed products) and certain internal conditions of the metal, the samples may be split longitudinally and etched deeply in hot hydrochloric acid (1:1). The presence of a pipe, segregation, and other defects will be revealed when a transverse section is etched. The interpretation of results should rest with those of experience in reading the effects of this test. For details, interpretation of results, and the correct etching time, see in this Handbook the Standard Macro-Etch Test for Iron and Steel.

Microstructure—The microstructure of the metal is studied to determine the internal condition of the metal, structure, and heat treatment. Photomicrographs at appropriate magnification record the conditions found. This method of testing is of much importance in determining the quality of sections, but the interpretation of results should be placed in the hands of experienced and trained technicians.

Inspection of Protective and Decorative Coatings—A protective coating may or may not be decorative. A decorative coating, however, must always be protective, because any coating which is not sufficiently protective soon loses its decorative quality.

The decorative quality of coatings is usually determined by visual examination.

The protective quality of a coating may be tested in several ways: (1) Outdoor exposure test, (2) salt spray test, (3) measuring the thickness of coating, (4) porosity test, and (5) the trichloroacetic acid test.

1. **Outdoor Exposure**—The outdoor exposure test, while quite reliable, usually involves more time than is permissible.

2. **Salt Spray**—The salt spray test is in general use for checking the corrosion resistance of coatings. The test should be conducted in a closed cabinet in which a solution of salt (NaCl), 20% by weight, is atomized continuously so as to give a visible fog in all parts of the cabinet. Pieces under test should be suspended or supported in such a manner that the solution will not be retained in pockets. The temperature should be approximately 70°F. The pieces which are to be tested should be free from all protective films other than the protective coating in question. The pieces should be left in the salt spray test until the first appearance of corrosion of underlying metal. The salt solution should be changed frequently to avoid concentration by evaporation or contamination with zinc chloride or iron chloride.

3. *Measuring the Thickness of Coating*—To determine if the coating is of sufficient thickness to give satisfactory protection, it may be measured under a microscope, by micrometer, or by chemical determination (strip tests). These tests are frequently used as a guide to coating practice.

4. *Porosity Test*—Coatings may also be tested for porosity. Porous coating, even though of sufficient thickness, will result in early failure. Porosity of coating is usually determined by microscopic examination or by means of ferroxy or similar papers.

5. *Trichloroacetic Acid or Porosity Test*—This test indicates porosity of nickel and tin plates over brass, bronze, or other copper alloys by the appearance of a blue color on immersing the part in a solution of 100 g. trichloroacetic acid and 700 cc. water.

At time of making the test add $\frac{1}{2}$ volume of ammonium hydroxide, sp.gr. 0.90, to one volume of the above stock solution. This solution should be used only once and should be discarded after making one test.

Chromium plated parts shall have the chromium plate removed before making the test. This may be done by immersing in hydrochloric acid until gas is no longer evolved, which signifies that the chromium is completely removed.

The time required for the blue color to appear is the measure of the quality of the plating from the standpoint of porosity.

Distribution of Results—It is known that when the results of testing many pieces of the same composition and heat treatment are plotted, the results tend to conform to the normal exponential distribution law. Therefore, it is impossible to specify too narrow ranges on any measured property without making allowance for the fractions having extreme values.

Thus, for example, in determining the Brinell hardness limits of a product with a 50-point range in a specification, 95% of the results might be found within the range. If only 40 points are allowed, only 85% might be included, and if only 30 points are allowed, only 70% may be found within the range.

Analytical Methods for Steel*

Explanatory Remarks—The methods described in this article are those selected after a critical study of the routine methods in use in several different laboratories as well as those adopted as referee methods. Of the former, only those that give results in close agreement with the latter have been included. Lack of space compels the omission of many details of manipulation and of the many variations that may be used in carrying out some of the procedures. To the well trained analytical chemist, these omissions are not essential, but when more complete details are required, the reference works given should be consulted.

Sampling—In commercial practice, particularly, the importance of care, good judgment, and cleanliness in sampling cannot be overemphasized, for it is self-evident that the most accurate analysis of a misrepresentative sample is worthless. Therefore, the sample must be taken in such a manner that it will be representative of the material sampled, and it must be prepared for analysis in such a way that it will be kept absolutely free of foreign material of any kind. Sampling of the molten steel as it is being cast into ingots affords the best opportunity, for obtaining a sample representative of the average composition, provided no additions are made to the steel in the molds. After the steel has been cast and forged or rolled the sample must be taken by milling or drilling. In general, milling of a complete cross section from a number of pieces selected from the lot is most satisfactory, particularly for small sections. To obtain a representative sample by drilling requires good judgment, as the method of taking the sample must be varied according to the kind of steel and the size and shape of the section. As a rule flats and shapes are sampled by drilling through the piece, and large sections by drilling in one or both ends, from some point corresponding to the locus of points midway between the center and the surface of the ingot.

Reagents—To save space reagents are designated by their chemical formulas, which are to be interpreted as representing either C.P. or reagent grade in solid or concentrated form as supplied by the manufacturers, chemically pure reagents being used for all standard solutions. Diluted solutions of the reagents are indicated in the several ways common to the profession. All water used is distilled water free from solids and having a pH value of 6.6 to 7. The pH of water saturated with CO_2 at room temperatures is near 5.

Determination of Carbon—Method and Limits of Error—Carbon in all kinds and types of steel is determined by direct combustion in oxygen. In routine and commercial analyses, the permissible variation in results from different laboratories is $\pm 0.01\%$, while results on the same sample of steel by the same laboratory should check to $\pm 0.005\%$. In referee work a tolerance of $\pm 0.005\%$ is permissible, because the limit of accuracy of the method for many kinds of steel is on the order of $\pm 0.003\%$. In analyzing steels containing less than 0.05% carbon, the limit of accuracy must be closely approached. Chemical knowledge, manipulative skill, and experience are required to obtain such accurate results on all classes of steel. Hence, except in referee work, carbon over 0.05% is reported only to the second decimal place.

Principle of the Method—Many variations as to details are permissible in both the apparatus and reagents used without exceeding the limits of error as noted above. The essential requirements are that a clean and representative sample of the steel be completely burned or oxidized in a stream of oxygen free of interfering substances and that the CO_2 resulting from this combustion be accurately measured. To measure the CO_2 evolved, it must be separated from other products of the combustion, particularly the oxides of sulphur and selenium, and from the excess oxygen. This separation is accomplished by removing the oxides of sulphur and selenium in an appropriate purifying train and absorbing the CO_2 from the excess oxygen in a suitable absorbing medium. The CO_2 is then measured either by weighing or by titrating with a standard acid. The direct gravimetric method is the favorite for both routine and referee work, and the following description is restricted to it and one volumetric method.

*Prepared by C. B. Francis, Chairman of the Subcommittee on Chemical Methods. The following contributors very kindly supplied methods for the preparation of this article: J. P. Gill, A. B. Frost, D. P. Bartell, C. H. Flickinger, F. R. Tyson, H. E. Slocum, C. W. Kneff, and T. S. Woodward.

Apparatus and Reagents—The essential parts of the apparatus used in this method are shown in Fig. 1. Apparatus and reagents suitable for use in the different parts of the train are as follows:

A. **Oxygen Supply**—Compressed or liquid; 99.5% O_2 ; free of CO , CO_2 , or any other carbon bearing matter. Must not contain hydrocarbons.

B. **Reducing Valves**—Several different types are manufactured.

C. **Oxygen Purifying Train**—Soda asbestos followed by anhydrous soda lime; followed by anhydrous $CaCl_2$; KOH followed by H_2SO_4 and $CaCl_2$ in order; or concentrated H_2SO_4 followed by KOH and $CaCl_2$. H_2SO_4 is renewed as soon as it becomes noticeably discolored.

D. **Mercury Trap**—Used to prevent back flow of oxygen.

E. **Electric Furnace**—A furnace capable of giving temperatures from 1000-1400°C. is preferable. Temperatures of 1000-1100°C. are satisfactory for carbon steels, provided the sample is composed of chips fine enough to pass a No. 10 sieve. For coarse drillings or chips and heat resistant alloy steels, a temperature of 1260°C., 2300°F., is most satisfactory.

F. **Rheostat**—Used for controlling temperature within operating limits. Several commercial types are available; must be adapted to current used and voltage.

G. **Pyrometer**—Determines the temperature of furnace within heating chamber external to the combustion tube. Temperatures up to 950°C. can be judged by eye, but not higher temperatures, which are in the white heat range.

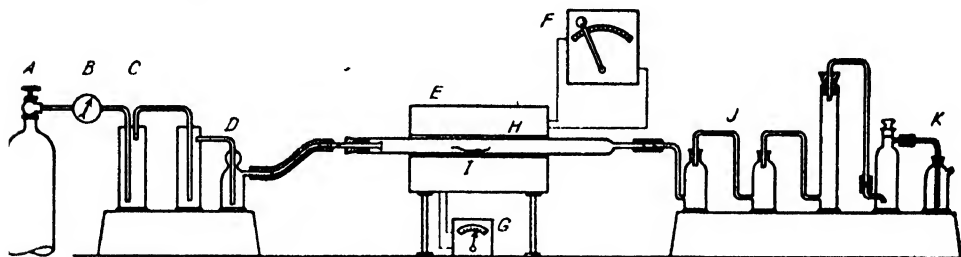


Fig. 1—Schematic diagram of carbon combustion train for the gravimetric determination of carbon in steel.

H. **Combustion Tube**—The best size is 1 in. inside dia. x 28 in. Exit end reduced in diameter is desirable. Tubes of quartz are satisfactory for temperatures up to 1050°C. For higher temperatures tubes must be made of porcelain or refractory clay glazed to be gas tight and nonsoftening at temperature of operation. Inlet end of the tube is preferably provided with a metal breech connector; if a rubber stopper is used it should be provided with a suitable shield, or the end of the tube should be water cooled. For low sulphur (under 0.060%) steels, the last 2 or 3 in. of the exit end of the tube may be packed with ironized asbestos to oxidize and hold sulphur and iron oxide, but the sulphur must be burned out regularly (every 200 determinations) by drawing this end of the tube back into the furnace while passing O_2 . For high sulphur and alloy steels, the asbestos packing is not desirable, except for those containing selenium, the oxides of which are most effectively removed by such a packing if the temperature is held below 200°C.

I. **Boat and Lining**—Boats are made of porcelain, refractory clays or 18 gage sheet nickel (max. carbon 0.02%). If nickel is used, it is ignited at 900-1000°C. for 8 hr. or longer after forming. Approximate size outside, $\frac{3}{4}$ in. wide at top, $\frac{1}{4}$ in. deep, 4-6 in. long, with walls as thin as practicable.

The boat is lined with alkali-free alundum, 60-90 mesh, or with highest grade chromic oxide, crushed, sized, washed, dried and ignited. Both boat and lining must be thoroughly ignited and kept protected from dust and other foreign matter before using for a combustion.

J. **Purifying train for removing H_2O and oxides of sulphur and selenium**—For low sulphur steels (under 0.06%) with tube, H, packed with ironized asbestos, this train may consist of a tube packed with P_2O_5 , but the same drying agent is also placed in the CO_2 absorber. For high sulphur steels (over 0.06%), selenium steels, and alloy steels requiring high temperature, this part of the train must provide for

the removal of oxides of these elements. Details may be varied to suit conditions. Combinations that have given satisfactory results for the direct gravimetric method are: (1) Zinc shot (40 mesh) followed by CaCl_2 and P_2O_5 ; (2) glass wool, PbO_2 , zinc shot, dehydrite; (3) heated platinized silica gel followed by ironized asbestos and P_2O_5 or other desiccant (Slocum sulphur trap); (4) specially prepared MnO_2 followed by dehydrite, anhydron, or phosphorus pentoxide; and (5) a 50% solution of chromic acid in water preceded by a packing of asbestos for selenium steels and followed by dehydrite, or by H_2SO_4 and dehydrite. The last three are especially recommended, and, with the exception of No. 3, are easy to prepare. In the volumetric method, the drying agents are omitted.

Preparation of Slocum Silica Gel Catalyst and SO_2 Absorption Tubes—Pour 90 ml. of a 10% solution of platinum chloride upon 120 g. of silica gel (wheat size), stirring to coat evenly. Dry at 110°C ., and cool. Add 40 ml. formaldehyde (40%), heat to 110°C ., and repeat till the gel is of a uniform black color. Cool, wash until free from chlorides, and dry at 110°C . Pack the platinized gel loosely into a U-tube, 1.2 cm. I.D. x 30 cm., total length, with a wad of glass wool at each end. Connect one end of the U-tube to the combustion tube, surround with a heating coil to maintain optimum temperature of 440°C ., and connect the other end to the SO_2 tube, the latter being packed with ironized asbestos, glass wool, anhydron, and glass cotton, in the end connected to the CO_2 bulb.

K. Absorber Bulbs for CO_2 —Direct Gravimetric Method—Types known as the Fleming, Nesbitt, Miller, Midvale, and Newburgh are acceptable. Closed types are recommended. The weight of the absorber packed should not exceed 200 g. and another of the same type should be used as a counterpoise in weighing. The bottle is packed from the bottom up with glass wool, soda lime or soda asbestos, a thin layer of asbestos, the same desiccant as is used before it, and glass cotton. Soda asbestos, or ascarite, is recommended. A newly packed bulb is first aspirated with oxygen, then allowed to stand in the balance case 5 min., and weighed just before using.

Volumetric Method—The absorber consists of a 300 ml. Erlenmeyer flask and a modified Meyer bulb of 10 sections, one end of which carries a glass tube long enough to reach the bottom of the flask when inserted through a 2-hole rubber stopper. This tube is slightly bent so that when the bulb is inserted in the stopper the tube is parallel with the side of the flask. In operation the barium hydrate solution is introduced into the Erlenmeyer flask which is then connected through the second hole of the stopper to the combustion train and supported in an inclined position so that the tube on the end of the Meyer bulb is below the surface of the barium hydrate solution. An improved form of bulb consists of 8 sections, the first 7 of which are $1\frac{1}{4}$ in. in diameter outside and the last $1\frac{1}{4}$ in. to serve as a splash bulb to prevent the solutions from being carried out of the bulb. The first 7 sections of this bulb have a capacity of 50 ml., the volume of barium hydrate solution recommended in these methods.

L. Gas Flow Indicator—The functions of this item are to guard the absorber and to indicate the gas flow, which must not be permitted to cease during a combustion. They may be of the pressure gage type or of the bubble type. Concentrated H_2SO_4 is generally used in the latter.

Checking the Train—The train assembled ready for operation should be checked before use and regularly thereafter for leaks and blank. The blank is found by placing the boat, containing only the lining, in the tube and passing oxygen as in a determination. The train may not be used for routine work until the blank is 0.0005 g. or less, and correct result (tolerance $\pm 0.005\%$) is obtained on an authoritative standard sample. In referee work 2-3 blank determinations, omitting only the sample in the boat, should be made prior to each determination to establish the blank.

Weight of Sample—To simplify calculations some multiple of the factor $0.2727 \left(\frac{\text{O}}{\text{CO}_2} \right)$ is used, usually 1.3635 g. or 2.727 g., the latter for low carbon steels.

These are known as factor weights.

Use of Accelerators with the Sample—Before high temperature furnaces were available, various substances called accelerators were added to the sample to effect complete combustion and liberation of all the carbon. With a high temperature furnace, giving working temperatures over 1200°C ., the use of an accelerator is seldom

necessary, except for certain high alloy steels, when 0.5-1.0 g. of pure tin shot (20-40 mesh) is added, and has been proved the best yet found for the purpose.

Procedure—Direct Gravimetric Method—With the train properly set up and tested, boat and absorbing bulb prepared, proceed as follows: Spread a suitable factor weight of the sample upon the bedding in the boat. If the combustion must be made at temperatures under 1100°C ., or if the sample is of a high alloy steel, add 0.5-1.0 g. of tin shot as an accelerator. Insert the boat into the end of the tube and push forward 2 or 3 in., but not far enough to coat the cuttings with oxide. After allowing 1-2 min. for the boat and contents to warm, push forward to the hottest part of the tube and close the latter at once. Admit oxygen at the rate of about 400 ml. per min. until combustion is complete (2-3 min.), then reduce the flow to about 200 ml. for 5 min. Close the oxygen valve, disconnect the absorber bulb, let it stand in the balance case 3 or 4 min., then close and weigh it. The gain in weight of the bulb (minus the blank in referee work), multiplied by 20 or by 10, depending upon the factor weight used, gives the per cent carbon.

In the meantime, remove the boat and place it under cover to cool. If the sample has not been completely oxidized to give a thoroughly fused button or "pig", repeat the determination.

Volumetric Method—To permit the use of a constant volume of barium hydrate solution, the weight of sample is varied from 1-5 g. inversely with the carbon content. Introduce exactly 50 ml. of standard barium hydrate solution into the absorber and connect it to the combustion train. Place a proper weight of sample in the boat, insert the latter into the combustion tube as described above, and admit oxygen as rapidly as the gases can be bubbled through the barium hydrate solution. Keep the gas bubbling through the bulbs during the combustion, and immediately after reduce the flow to that at the start. Aspirate 5 min., then disconnect the absorber, wash down Meyer bulb with CO_2 free water, add 3 drops of phenolphthalein indicator solution and titrate with standard HCl solution to the complete disappearance of pink color. Subtract the number of ml. of acid used from the number used in a blank titration and multiply the difference by the factor corresponding to the weight of sample used, to find the per cent carbon.

Solutions and Blanks for the Volumetric Method—Barium Hydroxide Solution—Dissolve 11 g. of $\text{Ba}(\text{OH})_2$ in 250 ml. of boiling water. Cool, filter rapidly, dilute to 1000 ml. with CO_2 free water, and keep protected from unpurified air until used.

Hydrochloric Acid—Dilute 6 ml. of concentrated acid to 1000 ml. To standardize these solutions proceed as follows:

Introduce 50 ml. of the $\text{Ba}(\text{OH})_2$ solution into the Erlenmeyer flask, add 100 ml. of CO_2 free water, and titrate with the HCl solution, using phenolphthalein as indicator. Record the ml. of HCl used as the blank. Now run two or more samples of a standard steel as in a regular determination. Subtract the average of the closely agreeing results from the blank, and divide the difference by the known per cent of carbon in the standard steel to obtain the carbon factor of the solutions. This factor must be determined for each new lot of solutions made up.

Determination of Manganese—Manganese is determined by the bismuthate or the persulphate oxidation methods, both of which are equally accurate when properly applied and carried out. In routine work the limit of accuracy that can in general be expected is $\pm 0.01\%$, in referee work $\pm 0.005\%$. Hence, manganese is reported to the second decimal place.

In both methods the manganese, after separation from interfering elements, is oxidized to permanganic acid, which is titrated with ferrous sulphate solution (bismuthate method) or with sodium arsenite (both methods). This titration may be made visually or potentiometrically, the latter being an advantage when the solution is colored or manganese to be titrated is high (over 15 mg.). For obvious reasons, the following descriptions are restricted and adapted to the visual method of titration.

Apparatus, Solutions and Reagents Required

I. **For the Bismuthate Method—Apparatus**—200 and 400 ml. beakers, two accurately calibrated 50 ml. burettes, heaters and suction filtering equipment.

Dilute Nitric Acid (sp.gr. 1.135)—Dilute 280 ml. of HNO_3 (sp.gr. 1.42) to 1 l.

Dilute Nitric Acid (3%)—Must be free of nitrous fumes. Boil 40 ml. of the concentrated acid; cool, and bubble clean pure air through it for 5 min.; dilute to 1000 ml., add 1 g. sodium bismuthate and allow to settle. Keep in a cool, dark place.

Asbestos Filter—Shred asbestos; ignite gently; digest with HCl; wash with H₂O in a ribbed funnel with platinum cone; digest 5 hr. with HNO₃ (1:3); wash thoroughly with hot H₂O, and mix with water. To make filter use a carbon filter tube. Add enough asbestos suspension to make a thin tight filter, apply suction gently, and wash thoroughly with hot water, and the 3% nitric acid. Then wash with KMnO₄ solution and with the dilute HNO₃ till washings are colorless.

Bismuthate—Must contain active O₂ equivalent to 75% NaBiO₃, and be free of Mn and Cl.

Ferrous Ammonium Sulphate—Dissolve 12 g. Fe(NH₄)₂(SO₄)₂·6H₂O in a cold solution of 50 ml. H₂SO₄ (sp.gr. 1.84) in 950 ml. of H₂O.

Standard Potassium Permanganate Solution (0.03 N)—Dissolve 1 g. KOH in 1000 ml. and add 1 g. KMnO₄. Age 1 week and filter through purified asbestos pad. Dissolve 1 g. of Bureau of Standards sodium oxalate in 100 ml. of boiled and cooled 5% H₂SO₄ solution. Titrate cold with the KMnO₄ solution, stirring constantly, heat to 70°C. and add the last 0.5 ml. dropwise to a lasting pink end point. Titrate a blank H₂SO₄ solution in the same way, and subtract this blank from the ml. KMnO₄ solution used to titrate the oxalate. Calculate the manganese value of 1 ml. of the KMnO₄ solution. A normal solution of sodium oxalate = 67 g. per l. and 1 ml. of N KMnO₄ = 0.01099 g. Mn, or 1 ml. of 0.03 N KMnO₄ = 0.0003296 g. Mn.

Standard Sodium Arsenite Solution—Dissolve 2 g. of pure sodium arsenite in water, filter if necessary, and dilute to 1 l. Standardize against 20 ml. portions of the standard KMnO₄ solution in 100 ml. of the filtered 3% HNO₃ solution, to a clear greenish yellow end point, or against standard steels, one containing no chromium and the others about the same as the steels to be analyzed.

II. For the Persulphate Method—Standard Sodium Arsenite—Make up solution as above. Standardize against a standard steel. To standardize against standard KMnO₄ solution, add 20 ml. of the latter to a 200 ml. beaker with 1 g. of electrolytic or ingot iron of low but known manganese content, and run through as in a regular determination. The solution is adjusted so that 1 ml. = 0.1% manganese on 0.5 g. sample, or 0.05% on a 1 g. sample.

Acid Mixture—Add 200 ml. H₂SO₄ (1:1) to 425 ml. of H₂O, then add 125 ml. H₃PO₄ (85%) and 250 ml. of HNO₃ (sp.gr. 1.42).

Silver Nitrate—Dissolve 10 g. of AgNO₃ in 1000 ml. of H₂O.

Ammonium Persulphate—Dissolve 25 g. of (NH₄)₂S₂O₈ (95% or better) in 85 ml. of H₂O, and use fresh.

Zinc Oxide Emulsion—Mix water with pure finely powdered zinc oxide, rubbing to a paste in a mortar at first, until it is of about the consistency of cream.

Sodium Bicarbonate Solution—Dissolve 80 g. of NaHCO₃ in 1000 ml. of H₂O.

I. Bismuthate Method—Plain Carbon Steel, and Low Alloy Steels Containing Nickel, Molybdenum, and Not More Than 3% Chromium—Dissolve 1.0 g. of sample (2 g. for ingot iron and 0.2-0.5 g. for manganese steel) in 50 ml. of HNO₃ (sp.gr. 1.135) and add the same acid to another beaker for a blank. Boil till oxides of nitrogen are expelled, then cool and add NaBiO₃ until a decided pink color persists on heating to boiling. Boil 2 min., add SO₂ or NaNO₂ solution until clear, and continue boiling until free of oxides of sulphur or nitrogen. Cool to 15°C., add an excess of NaBiO₃, shake or stir for 1-2 min. and let stand about 3 min. Add 50 ml. of the 3% HNO₃ and filter through an asbestos pad or, preferably, a fritted glass filtering crucible, porosity 1-G-4. Wash with the 3% HNO₃ until washings are colorless, and (a) titrate with ferrous sulphate and permanganate if chromium is low or absent, or (b) with sodium arsenite if chromium is high.

(a). Add 3 ml. of H₃PO₄ and completely discharge the pink color with ferrous ammonium sulphate solution. Back titrate with standard KMnO₄ solution to a lasting faint pink end point. Add the same volume of ferrous ammonium sulphate solution to the blank and titrate with the standard KMnO₄ solution. Subtract the ml. of KMnO₄ used in the first titration from that of the blank, and multiply by the proper factor to give the per cent manganese in the sample.

(b). Add standard sodium arsenite solution rapidly until the pink color starts to fade then slowly to a clear greenish yellow color that does not change on addition of another drop of the arsenite.

(2). **Chromium-Vanadium and Stainless Steels**—Separate chromium and other interfering elements by (a) zinc oxide, (b) a bicarbonate, or (c) an ammonium persulphate separation, the first being preferred except when cobalt is present, where the last must be used.

(a). Dissolve 2 g. of sample in 40 ml. dilute H_2SO_4 (1:3), add 30 ml. dilute HNO_3 (sp.gr. 1.135), and boil free of fumes. Cool, transfer to a 250 ml. volumetric flask, partly neutralized with dilute ammonia (1:3) if preferred, and add zinc oxide emulsion with shaking until a heavy buff colored precipitate forms. Dilute to the mark, shake, allow precipitate to settle, and filter off 125 ml. of the clear solution through a dry filter, collecting the filtrate in a carefully calibrated flask. Transfer this filtrate to an Erlenmeyer flask, add 25 ml. of HNO_3 (sp.gr. 1.42), boil free of oxides of nitrogen, and continue as in (1) above, but do not dilute before filtering.

(b). Dissolve 1 g. of sample in 20 ml. of dilute H_2SO_4 (1:9) contained in a covered 300 ml. Erlenmeyer flask, and dilute to 100 ml. with boiling water. Immediately add from a burette sodium bicarbonate solution until a permanent precipitate forms, then 4-6 ml. excess according to the chromium present. Filter through a 11 cm. paper, and wash 2 or 3 times with hot water, ignore cloudiness in the filtrate. Heat filtrate to boiling, add gradually 12 ml. of HNO_3 (sp.gr. 1.42) and evaporate to about 25 ml. Complete the determination as in (1) above. A trace of manganese may remain on the filter, particularly if it is high, and too great an excess of the bicarbonate solution is added. Practice on standards is necessary to develop the proper technique.

(c). Dissolve 1 g. of sample in a 400 ml. beaker with 15 ml. of a mixture of equal parts of HCl and HNO_3 . Add 20 ml. of HClO_4 , evaporate to fumes, and fume strongly for 10 min. Dilute to about 250 ml. with hot H_2O , add ammonia until iron is just precipitated, then 5-10 g. of ammonium persulphate and 10 ml. excess ammonia to precipitate manganese. Boil 10 min., let settle, filter and wash with hot dilute ammonia. Dissolve precipitate with dilute HNO_3 to which sodium nitrite has been added or with dilute H_2SO_4 (1:9) saturated with SO_2 , and complete the determination as described in (1a or 1b) above. If cobalt is high, boil and reprecipitate with ammonia and ammonium persulphate before oxidizing the manganese.

II. Persulphate Arsenite Method—The procedure below is applicable to all alloy steels, except (a) those containing more than 3% chromium, (b) those containing more than 10% nickel, (c) the chromium-tungsten steels, and (d) low tungsten steels. For these steels the initial treatment is varied as follows:

(a) For manganese in stainless and heat resistant steels, the chromium is most conveniently separated by volatilization as follows: Transfer 0.5 g. of sample to a 250-ml. Erlenmeyer flask. Add 5 ml. of dilute HCl (1:1) and 20 ml. of HClO_4 (70%). Heat gently until the steel is dissolved and fume to oxidize the chromium completely. Cool slightly and add a small portion of NaCl or HCl , then fume again. Repeat these operations until the solution ceases to evolve brown fumes of chromyl chloride when the chloride is added. Rinse the wall of the flask with a fine jet of water, add 5 ml. of HClO_4 (70%), and fume to expel chlorides completely. Cool slightly, add 25 ml. of the acid mixture, dilute to 100 ml. with hot water and complete the determination of manganese as directed in the procedure below.

If care is exercised to expel all the chromium, the solution may be used for the direct determination of vanadium, or any other element except those forming volatile chlorides. Also, the chromium may be separated from the perchloric acid solution with lead perchlorate, and most of the perchloric acid in turn removed by adding potassium phosphate.

(b). Separate Cr as in 1-2 (a) or (b), add 30 ml. of the H_2SO_4 - H_3PO_4 - HNO_3 mixture to the filtrate, or an aliquot part thereof, evaporate to 100 ml. and proceed as directed in the procedure below.

(c). Separate manganese by dissolving in HNO_3 , precipitating with KClO_4 , and filtering on asbestos, or by proceeding as follows: Dissolve 0.5 g. of the sample in 12 ml. of dilute H_2SO_4 (1:9), immediately dilute to 100 ml. with boiling water, add 10 g. or more of ammonium persulphate, boil 10 min. and filter. In either case dissolve precipitate with dilute nitric acid containing sodium nitrite, boil, add 30 ml. of the acid mixture and proceed as directed under Procedure below.

(d). Heat 0.5 g. of sample with 50 ml. of dilute H_2SO_4 (1:9) and 3 ml. H_3PO_4 , add 30 ml. of H_2O and 5 ml. of HNO_3 , and boil till solution is complete, then proceed as for the solution below:

Procedure—Transfer the sample (1 g. or less for Mn up to 1.00% or 0.5 g. or less for higher percentages) to a 500 ml. Erlenmeyer flask, add 30 ml. of the H_2SO_4 - H_3PO_4 - HNO_3 mixture and warm till dissolved. Boil till oxides of nitrogen are expelled, then add 100 ml. of hot water, 10 ml. of AgNO_3 solution, and 10 ml. of $(\text{NH}_4)_2\text{S}_2\text{O}_8$ solution. Boil briskly 1 min. Cool to below 30°C . and titrate rapidly

with standard sodium arsenite solution to a clear yellow end point that does not change on adding another drop of the arsenite solution. Multiply the ml. of arsenite solution used by the proper factor to find the per cent manganese in the sample.

Determination of Phosphorus—Phosphorus is always separated as ammonium phospho-molybdate, following which separation it may be determined by titrating with standard NaOH and HNO₃ solutions or gravimetrically by redissolving and reprecipitating as magnesium ammonium phosphate, the former method being used in routine analyses and the latter in referee work. For steel of all kinds, the accuracy is on the order of $\pm 0.005\%$, yet long custom decrees that results for this element be reported to the third decimal place.

Solutions Required

Dilute Nitric Acid (sp.gr. 1.20)—Dilute 380 ml. of HNO₃ (sp.gr. 1.42) to 1 l.

Dilute Nitric Acid (2%)—Dilute 20 ml. to 1 l.

Potassium Permanganate—Dissolve 25 g. of KMnO₄ in 1 l. of water.

Ammonium Bisulphite—Dissolve 30 ml. in 1 l. of water.

Ammonium Nitrate—Dissolve 50 g. in 1 l. of water.

Potassium Nitrate—Dissolve 10 g. in 1 l. of water.

Dilute Ammonia—Dilute 50 ml. of NH₄OH (sp.gr. 0.90) to 1 l.

Ammonium Molybdate Solution—Mix 55 g. of MoO₃ (or 65 g. of 85%) with 150 ml. of H₂O and dissolve by slowly adding 150 ml. of NH₄OH (sp.gr. 0.90) while stirring constantly. Filter, if not clear, and add slowly to 750 ml. of cold dilute nitric acid (sp.gr. 1.20) while the latter is constantly agitated. Add 2 drops of a saturated solution of ammonium phosphate solution, let stand 24 hr. and filter.

Some prefer a neutral molybdate solution made by mixing 65 g. of (NH₄)₂MoO₄·4H₂O, 225 g. of NH₄NO₃, 15 ml. of NH₄OH, and about 600 ml. of water, warming, filtering, and diluting to 1000 ml.

Phenolphthalein Indicator Solution—Dissolve 0.3 g. in 100 ml. ethyl alcohol (50%) and neutralize with standard NaOH solution.

Standard NaOH Solution—Dissolve 6.6 g. of NaOH in 1 l. of water, add 1 ml. of a saturated solution of Ba(OH)₂ and let stand 24 hr. or longer. Filter rapidly into a container and keep protected from the air with a soda lime tube. Standardize against an authoritative standard steel, preferably of a composition similar to the steels to be analyzed. Adjust so that 1 ml. = 0.01% phosphorus on a 2 g. sample.

Standard Nitric Acid—Clear the concentrated acid (sp.gr. 1.42) of oxides of nitrogen by boiling or bubbling pure air through it and dilute 7 ml. to 1000 ml. Dilute to agree with the Standard NaOH solution.

Magnesia Mixture—Dissolve 50 g. of MgCl₂·6H₂O and 100 g. of NH₄Cl in 500 ml. of H₂O. Add a slight excess of ammonia, let stand 12 hr., filter if not clear, and make just acid with dilute HCl. Some use the sulphates, but the chlorides are best.

I. Procedure—Volumetric Molybdate; NaOH Method—1. *Carbon Steels*—Transfer 2 g. to a 300 ml. Erlenmeyer flask, and dissolve with 50 ml. dilute HNO₃ (sp.gr. 1.20). For very low phosphorus, use 4 g. of sample and increase the acid to 75 ml. Also, increase the volume of acid if it is more dilute or if neutral ammonium molybdate is to be used. With the latter and acid of 1.35 sp. gr., for example, use 120 ml. of acid for a 4 g. sample. Add an excess of KmnO₄, boil 2 min., and clear the solution by adding ammonium bisulphite solution dropwise. Boil free of oxides of nitrogen, cool to 65–70°C., and add 50 ml. of molybdate solution at 20–25°C. Mix thoroughly, cool, and shake, preferably mechanically, for 10 min. Allow the precipitate to settle and filter through a close filter, washing the precipitate out of the flask with 2% nitric acid. Wash the flask and filter free of acid, the latter about 10 times, with the KNO₃ solution. Transfer the filter and precipitate to a titrating tumbler, add about 25 ml. of H₂O and standard sodium hydroxide solution in slight excess. Thoroughly macerate the paper with a stirring rod, dilute to about 150 ml., add 3 drops of phenolphthalein indicator solution, and titrate the excess NaOH with the Standard Nitric Acid Solution. Subtract the ml. of acid from the ml. of NaOH solution used to find the phosphorus in hundredths of a per cent.

II. Alloy Steels—Tungsten and Vanadium Absent—Procedure A—Transfer 2 g. to a 300 ml. Erlenmeyer flask, add 40 ml. of dilute HNO₃ (sp.gr. 1.20) and heat gently. If the steel does not dissolve or the solution becomes dark or black, add

5 ml. HCl and continue heating till it is dissolved. Add 25 ml. HClO₄ (60%) and continue heating for 5-10 min. after fumes of HClO₄ have appeared, but avoid too high a temperature. If carbon or carbides do not dissolve, add a few crystals of NaClO₃ and boil for 5 min. after the last addition. Cool, add 40 ml. of H₂O, filter, wash, and add 25 ml. of dilute nitric acid (sp.gr. 1.20). The solution should be completely oxidized. To test it, add NaMnO₄ or KMnO₄ solution drop by drop until it is pink in color, the sodium salt being preferred on account of the low solubility of potassium perchlorate. Boil the solution, decolorize with the usual reducing agent added drop by drop, and cool somewhat. To provide abundance of ammonium nitrate and adjust the acidity, add ammonia until a slight precipitate forms, and acidify by adding an excess of 5 ml. of HNO₃. Cool, if necessary, to about 50°C., add 50-70 ml. of the ammonium molybdate solution, and complete as described in I above or in the gravimetric method given later.

Procedure B—The following procedure was developed many years ago and is still recommended for some steels, such as austenitic manganese and silicon steels.

Digest 2 g. of sample with 50 ml. dilute HNO₃ (sp.gr. 1.20) until action ceases. Evaporate and bake for 1 hr. at 190-210°C. Cool somewhat, add 25 ml. HCl, warm to dissolve the cake, and evaporate to a paste. To expel the chlorine, take up with 10 ml. of HNO₃, add 50 ml. of HNO₃, evaporate to the appearance of a slight scum, again add 50 ml. of HNO₃ and evaporate to the same point. Finally, add 50 ml. of HNO₃ (sp.gr. 1.20), heat gently till soluble salts are dissolved, filter, and wash with water containing a few drops of HNO₃ per l. Heat the filtrates and washings to boiling, oxidize with a few drops of 2% KMnO₄ solution, boil 2-3 min., clear the solution by adding ferrous sulphate solution drop by drop, boil 3 min., and cool. Add ammonium hydroxide until a slight precipitate forms, then acidify by adding 5-10 ml. of HNO₃, and proceed with the precipitation of the phosphorus as described above, adding a slight excess of ferrous sulphate and keeping the temperature of precipitation below 45°C. If traces of vanadium may be present.

3. *Alloy Steels—Vanadium Present, Tungsten Absent*—Treat as in 1 above up to the point of adding the molybdate solution, then cool to 15°C. instead of 60°C. and add 5 ml. of a 40% solution of FeSO₄·7H₂O. Shake, add 85 ml. of molybdate solution, and continue shaking for 10 min. Allow to stand at least 1 hr., preferably longer, and finish the analysis as in I above. Set the filtrate aside for 6-8 hr. to make sure all the phosphorus was precipitated.

4. *Alloy Steels—Presence of Tungsten*—Transfer 2 g. to a No. 4 casserole and add 20 ml. of HNO₃ and 40 ml. of HCl. Heat until all but WO₃ is dissolved, evaporate to dryness, and bake off excess acid. Cool, add 20 ml. of HCl, warm, add 40 ml. of H₂O, and boil 10 min. or longer. Filter into a 300 ml. Erlenmeyer flask and wash alternately 3 times with hot dilute HCl (1:1) and hot water and finally 3 times with hot water. Evaporate filtrate to 10-15 ml., add 20 ml. of HNO₃ and evaporate again. Repeat HNO₃ treatment, dilute and filter if not clear. Add ammonia (about 15 ml.) until iron precipitates. Add HNO₃ slowly while shaking until precipitate just dissolves, then add 3-5 ml. excess (about 20 ml.). If vanadium is absent adjust temperature to 65-70°C., add 50 ml. of molybdate solution and finish as in I above. If vanadium is present, cool to 15°C. and continue as directed in 3 above. Add to the final result 0.001% for phosphorus retained by the WO₃ precipitate.

II. **Procedure—Gravimetric Molybdate-Magnesia Method**—Treat 4 or 5 g. of sample as in I up to the precipitation of the phosphorus with molybdate solution and let stand 4 hr., or longer. Filter and wash flask and filter 3 times with 2% nitric acid, and 5 times with 5% ammonium nitrate solution. Dissolve precipitate into a 250 ml. beaker with 20 ml. of dilute ammonia (1:1) containing 2 g. of citric acid, and wash filter 5 times with dilute ammonia, 5 times with hot water and 5 times with dilute HCl (1:20). If solution is cloudy filter through same paper and wash with hot water. Burn off the paper in a platinum crucible, fuse with not more than 0.5 g. of Na₂CO₃, extract with 10 ml. of hot water, and filter into the ammoniacal solution. Evaporate to 75 ml., acidify with HCl, add 20 ml. of magnesia mixture, and cool in ice water. Make slightly ammoniacal, stir 5 min., add 5-10 ml. of ammonia and let stand in a cool place 6 hr. or longer. Filter, wash 3 times with dilute ammonia, and dissolve into original beaker with dilute HCl (1:1). Unless arsenic is known to be absent, add 1 g. of NH₄Br and boil down to 10 ml. or slightly less. Dilute to 75 ml., add 0.2 g. of citric acid and reprecipitate as before. After 6 hr. filter, preferably through a close paper containing a quantity of ashless

paper pulp, wash with dilute ammonia, and ignite slowly at first and finally to constant weight at 1050-1100°C. Weigh as impure $\text{Mg}_3\text{P}_2\text{O}_7$. Treat with HCl . If a residue remains, filter, wash with H_2O , ignite, and weigh. Add 4 or 5 drops HF , evaporate slowly, ignite, and weigh. Subtract any loss in weight of the residue from that of the impure $\text{Mg}_3\text{P}_2\text{O}_7$ and calculate difference to per cent phosphorus, using the factor 0.27861.

Determination of Sulphur—Sulphur, like phosphorus, is reported to the third decimal place, though if results on the same sample from different laboratories check within 0.005% for plain steel, or within 0.010% on some alloy steels, the work should be considered satisfactory except when the highest accuracy is desired.

This element is determined either volumetrically or gravimetrically, the procedures being entirely different in every respect. In general the volumetric method is applied whenever possible in routine work, and the gravimetric methods are used only for referee work and in the analysis of steels to which the volumetric method is not applicable, including all steels containing selenium and many high alloy steels, such as the Cr-W-V steels. During the last 12 years (1926-1938) several methods involving combustion in oxygen have been proposed and the method is now being employed to advantage for sulphur in certain alloy steels, but the method has not yet reached the standing of a standard procedure. It may become such in the future with the introduction of further refinements.

I. Volumetric Evolution Method—Applicable to carbon steels and to alloy steels which are rapidly dissolved by HCl and evolve all their sulphur as H_2S , facts that must be ascertained experimentally. Selenium and zirconium interfere. A few steels which fail to meet the essential requirement just mentioned can be made to evolve all the sulphur as H_2S by annealing the drillings as follows:

Wrap 5 g. of the drillings in an 11 cm. filter paper, place in a porcelain crucible, add a layer of sulphur free charcoal, cover tightly, heat for 20 min. at 950-1000°C., cool slowly and treat as described below.

Steels that dissolve slowly in dilute HCl , such as those high in copper, are dissolved in concentrated acid. Many steels will not evolve all their sulphur by any treatment and it is customary to apply a factor to the results obtained by this method, this factor being determined for each type of steel by analyzing a Bureau of Standards Standard Sample of the same type.

Solutions Required

Dilute HCl—Dilute 500 ml. (sp.gr. 1.19) to 1 l.

Ammoniacal Zinc Sulphate—Dissolve 100 g. of $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ in 500 ml. of H_2O and add 500 ml. of NH_4OH (sp.gr. 0.90). Filter.

Ammoniacal Cadmium Chloride—Dissolve 10 g. of CdCl_2 in 400 ml. of H_2O and add 600 ml. of NH_4OH (sp.gr. 0.90).

Starch Solution—Use a fresh wheat, potato, or soluble starch. Many lots, particularly of the last, have been found unsuitable. Make 5 g. into a thin paste with water and add slowly to 500 ml. of boiling water. Let stand 24 hr., decant clear solution, add 15 g. of KI and mix. Use within 2 or 3 days or add a preservative, usually 5 g. of ZnCl_2 or ZnSO_4 in 50 ml. of water.

Titration Solution—Either iodine or potassium iodate is satisfactory. Dissolve 4 g. of resublimed iodine or 1.12 g. of KIO_3 in a concentrated solution of 12 g. of KI and dilute to 1 l. It is standardized to the theoretical titer against Bureau of Standards sodium oxalate through 0.03N KMnO_4 solution, or directly against arsenious acid, and adjusted to a normality of 0.0312 so that 1 ml. = 0.01% sulphur on a 5 g. sample. When so standardized it is necessary to apply corrections for blank in all titrations. This drawback is overcome in practice by standardizing the solution against a standard steel of the same kind and type as the steel to be analyzed, but a solution thus standardized will in most cases give slightly erroneous results on steels much lower or higher in sulphur than the standard.

To standardize with arsenious oxide, dissolve 1.5435 g. of this oxide with 1.25 g. of NaOH in warm water, dilute to 1 liter, and titrate iodate as follows: From a burette, transfer 20 ml. of the KIO_3 solution to a 250-ml. Erlenmeyer flask, and add an excess of KI . (A stable 0.03119 N solution of KIO_3 is made by dissolving 1.1125 g. of the salt and 2 g. of NaOH in water and diluting to 1 liter.) Acidify by adding 2 ml. of HCl (1:1), rinse the wall of the flask thoroughly, and buffer the solution with 15 ml. of ammonium acetate solution (50%). Add KIO_3 solution to a clear colorless end point. With the theoretical titer a factor must be applied to all results,

1.05 being recommended as a reliable average for carbon steels. Applying this factor to the solutions gives a normality of 0.02963.

Apparatus—Fig. 2 shows a typical apparatus used.

Procedure—Transfer 5 g. of sample (some prefer 10 g.) to a sulphur flask and connect as shown in Fig. 2. To 150 ml. of water in the titrating tumbler add 10 ml. of the absorbent solution and introduce 80 ml. of HCl (1:1, 2:1, or concentrated) through the funnel tube. If the latter acid is used, equip the flask with a suitable type of return condenser. Heat gently until the sample is dissolved and boil ($\frac{1}{2}$ -1 min.) until the gas in the flask is displaced with steam. As soon as the delivery tube becomes hot to the touch, disconnect the flask and remove it from the heat, leaving the delivery tube in the absorber and titrating tumbler. If the solution in the tumbler has become warm, cool it to 20°C. or below. Place the tumbler under the titrating burette, add 5 ml. of starch solution and 40 ml. dilute HCl (1:1) and titrate immediately with the iodine or iodate solution to a permanent blue end point. The number of ml. of titration solution used, minus the blank, if theoretical titer is used, gives the sulphur in hundredths of a per cent. If the theoretical titer is used and a weight greater or smaller than 5 g., the number of ml. are divided by 100 times the weight of sample used and multiplied by 5 to find the per cent sulphur.

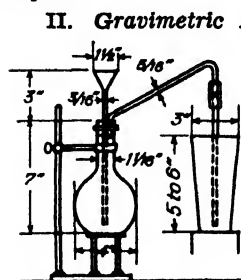


Fig. 2—Typical apparatus for determining sulphur by the evolution method. Left—sulphur flask. Right—absorber and titrating tumbler.

II. Gravimetric Methods—The gravimetric methods include those known as the nitric acid method, the Meinelke method, the ether method, and the fusion method. The first two are more commonly used in this country and are described below:

1. **Nitric Acid Method—Selenium Absent**—(a). **Carbon Steel**—Transfer 4.58 g. of sample to a 400 ml. covered beaker, add 50 ml. of HNO_3 and dissolve slowly by regulating the temperature. Start 2 blank determinations in the same way. Some also add about 1 ml. of Br or about $\frac{1}{2}$ g. of NaBr, or add the sample in small portions. When the steel is dissolved add 0.5 g. of NaNO_2 , if NaBr was not used, and evaporate to about 10 ml. Cool, add 30 ml. of HCl, and evaporate just to dryness. Then add 30 ml. more of HCl and evaporate to the first separation of ferric chloride and redissolve with about 5 ml. of HCl; or separate the HNO_3 by adding 40 ml. of HClO_4 (70%) and evaporate to fumes, fuming 10 min., and holding the temperature no higher than necessary. Dilute with 25 ml. of H_2O and reduce by adding an excess of sulphur-free zinc. Before the evolution of hydrogen ceases entirely filter and wash with 75 ml. of 1% HCl, heat to 70°C. and add 10 ml. of a 10% solution of BaCl_2 . Let stand 24 hr., filter on a close paper and wash the filter once or twice with cold 1% HCl and finally with hot H_2O until free of chlorides, keeping the washings separate. Evaporate washings to dryness. Take up residue in 1 ml. of HCl, dilute to 25 ml., add 1 ml. of BaCl_2 and digest at 80°C. for 5 or 6 hr. Filter on a close paper, wash free of chlorides with hot H_2O and ignite both papers in a weighed platinum crucible. Add 1 drop of dilute H_2SO_4 (1:1) and 1 ml. of HF and evaporate to dryness. Ignite and weigh as BaSO_4 . Subtract the average weight of the blanks and multiply by 3 to find the per cent sulphur.

(b). **Tungsten, Selenium, and Low Sulphur Alloy Steels Insoluble in Nitric Acid**—Provide for 2 blanks and proceed as follows: Dissolve 4.58 g. of sample by adding it a little at a time to a mixture of 50 ml. of HNO_3 and 45 ml. of HCl contained in a 600 ml. beaker, or, if tungsten steel, by adding it to the nitric acid, warming, and adding the HCl a little at a time. Evaporate to about 20 ml., add 30 ml. of HCl, evaporate to about 20 ml., add cautiously 2 g. of Na_2CO_3 (omit if tungsten is present) and evaporate to dryness. Bake at 100-105°C. about 15 min., cool, add 30 ml. of HCl and the same volume of water, and digest till soluble salts have dissolved. Filter and wash with hot dilute HCl (1:1) and hot water, and finally 3 times with hot water. Evaporate filtrate to dryness, and bake at 100-105°C. Add 20 ml. of HCl, warm and add 60 ml. of hot water. Stir and filter immediately through a close paper into a 200 ml. beaker. Wash with 2% HCl and hot water until free of iron stains, and finally 5 times with cold water. Add a small amount of fine paper pulp, stir in 20 ml. of 10% BaCl_2 solution and let stand 12 hr. or longer. Filter through a close double filter, and wash free of iron stains with a solution containing 10 ml. of HCl and 2 g. of BaCl_2 per l. Wash free of chlorides with a small jet

of hot water and ignite carefully to a red heat. Cool, weigh, test for SiO_2 as in II(a) above, deduct blanks and multiply by 3 to find the per cent sulphur.

2. *Copper-Potassium Chloride, or Meineke, Method*—For high sulphur alloy steels insoluble in HNO_3 . Generally, results by this method are low by 0.002% to 0.005% S.

Special Solution Required

Copper Potassium Chloride $2\text{KCl} \cdot \text{CuCl}_2 \cdot 2\text{H}_2\text{O}$	300 g.
Hydrochloric Acid	75 ml.
Water	1000 ml.

Add the salt to the mixture of acid and water.

Procedure—Start one blank with each sample until an average blank for each lot of chemicals is established. Add 2.748 g. of sample to 225 ml. of the double chloride solution at room temperature and stir mechanically until the metal is dissolved. Filter through a thin close pad of thoroughly purified asbestos and wash 3 times with warm 2% HCl solution. Transfer plug with residue to beaker. Add 25 ml. of H_2O and 2 g. of KClO_4 . Then add 10 ml. of HNO_3 and 20 ml. of HCl and heat to dissolve carbides, sulphides, and sulphur. Filter and evaporate filtrate just to dryness. Redissolve in 10 ml. of HCl , evaporate to dryness, and bake at about 110°C . for 20 min. Dissolve residue in 10 ml. of HCl and evaporate to 5 ml. Dilute to 100 ml. with water, bring to the boiling point and filter. Wash with warm water to a volume of 200 ml. To this filtrate add 20 ml. of a 10% filtered solution of BaCl_2 . Warm for 5 min. and let set overnight. Filter and wash with a cold solution containing 10 ml. of HCl and 20 ml. of 10% of BaCl_2 per l. Finally wash with hot water. Ignite and weigh as BaSO_4 . Subtract the blank and multiply by 5 to find the per cent sulphur.

Determination of Silicon—Various methods that have been used for the determination of silicon are the straight hydrochloric acid method, the straight sulphuric acid method, the nitric-sulphuric acid or "Drown's" method, the hydrochloric-sulphuric acid method, and the perchloric acid method. All can be applied to carbon steels, except the first, which requires application of a factor to results as obtained and cannot, therefore, be considered as a standard. Of the other methods all require some modification before they can be applied to tungsten steels, and those involving dehydration of the silica with sulphuric acid may give trouble when applied to some steels containing much chromium (over 3%) unless special precautions are taken to purify the silica.

Weight of Sample Used—To avoid calculations the use of factor weights are recommended, and in all methods the weight of sample is varied according to the silicon content. Therefore, use 4.672 g. ($10 \times$ the factor 0.4672) of steels containing less than 0.3% silicon, and 2.336 g. of steels containing more than 0.5% silicon. Between 0.3 and 0.5% either weight may be used.

I. *Methods Involving Dehydration of Silicic Acid with Sulphuric Acid*—Applicable to all steels except those containing tungsten and much chromium and carbon.

(a). *Procedure*—Transfer the sample to a 600 ml. beaker of the pyrex type, or to a 300 ml. casserole or evaporating dish of porcelain or platinum. If porcelain is used, select a vessel in good condition. Dissolve the steel with a large excess of HCl , HNO_3 , H_2SO_4 , or a mixture of H_2SO_4 and either of the other two, whichever does the work most quickly. When the metal has dissolved, add 25-40 ml. of H_2SO_4 (1:1), unless a mixture containing an equivalent amount of H_2SO_4 was used, and evaporate until copious fumes of H_2SO_4 are evolved, then push the salts beneath the acid with a rod and fume for 2 or 3 min. Cool somewhat, add 100 ml. of warm H_2O , stir until salts are dissolved, and filter immediately through a close paper. Scrub the container thoroughly with a policeman, and wash alternately with hot dilute HCl (1:20) and hot water, until salts are dissolved, and finally 3 times with hot water. In referee work, or if silicon is over 0.30%, evaporate the filtrate, fume, filter and wash as before to recover soluble silica. Transfer the filter or filters and contents to a clean, weighed platinum crucible, ignite carefully, cool and weigh as impure SiO_2 . Moisten this silica with 0.5-1 ml. of dilute H_2SO_4 , add 10-15 ml. of HF , and evaporate slowly in a bath of hot air. When the contents are dry, ignite as before, cool and weigh. The loss in weight represents pure silica, from which the per cent is obtained by multiplying by 10 or 20, according to the factor wt. used.

(b). *Procedure for Tungsten Steels*—Transfer 2.336 g. of the sample to a 375

ml. casserole and add 50 ml. of concentrated hydrochloric acid. Cover the casserole and heat until the sample is dissolved. Remove from the hot plate and add slowly 10 ml. of concentrated nitric acid. When violent action is over cover the dish and evaporate rapidly to dryness. When the solution is near dryness remove to a cooler side of the hot plate to avoid spattering, and bake to the absence of all fumes. After baking is complete, cool slightly and add 30 ml. of concentrated hydrochloric acid and 20 ml. of water. (If preferred 30 ml. of H_2SO_4 may be added, when the steel has been dissolved and treated with HNO_3 , and evaporated to fumes, cooled, mixed thoroughly with 5 ml. of HCl and taken up in 100 ml. of H_2O .) Heat and keep near the boiling point until all soluble salts have dissolved. Remove the dish from the hot plate, wash off the cover glass and adjust the volume to about 100 ml. with hot water. Filter on paper pulp with suction. Wash 4 times alternately with hot dilute hydrochloric acid (1:1) and hot water and finally 4 times with hot water. In special work evaporate the filtrate, filter and wash as before.

Place the paper containing the tungsten, silica and impurities in a 20 ml. platinum crucible and ignite at a dull red heat until the paper is gone and the residue in the crucible is yellow in color. Cool in a desiccator and weigh. Ignite again for 15 min. at a dull red heat to insure constant weight. Volatilize silica as directed above, finally igniting at a dull red heat, not over 800°C .

II. Method Dehydrating with Perchloric Acid—Applicable to all steels except tungsten steels.

Procedure—Transfer the sample to a 400 ml. beaker of heat resistant glass. Add 30 ml. of HNO_3 (1:3) and add if necessary to effect solution 5-10 ml. of concentrated HCl . Warm on the hot plate until sample is in solution, remove from the plate and add 30-50 ml. (according to the size of sample) of 70% perchloric acid, c.p. Cover with a watch glass, return to the hot plate and evaporate to heavy fumes of perchloric acid. Continue to heat for 10-15 min., keeping the liquid hot enough to maintain a steady reflux of the acid on the wall of the beaker. Cool, add 100 ml. of H_2O and warm until all soluble salts are in solution. Filter at once and rapidly (suction), using paper pulp, wash well with warm dilute HCl (2%), and complete the washing with hot H_2O .

Ignite carefully and thoroughly, as the HClO_4 , not washed out of the silicic acid may cause popping and loss of silica. Complete the determination as directed in I(a).

Determination of Silicon and Tungsten—Three satisfactory methods are used, which are as follows:

I. The $\text{HCl-HNO}_3\text{-Na}_2\text{CO}_3$ Fusion Method—This method is applied to steels containing 1-6% tungsten; for steels containing 1% or less, it is better to determine Si and W on separate samples.

Procedure—Transfer 2.336 g. (factor weight for silicon) to a 375 ml. casserole or an unetched heat resistant beaker, and treat as described for silicon in tungsten steels. After volatilizing silica and determining silicon, fill the crucible half full of sodium carbonate and heat at a low temperature for 5 min. At the end of this time raise the heat until the highest temperature of a Meker burner is attained and the contents of the crucible fuse. Maintain in quiet fusion for 5 min. longer. Grasp the crucible with the tongs and, by a slow rotating motion, spread the molten contents evenly up on the sides. When the fusion is solid, place carefully in a 250 ml. beaker containing 150 ml. of water. Digest at a temperature just below the boiling point until the fusion is disintegrated. Remove the crucible and heat until everything except the precipitate of iron is dissolved. Filter on an 11 cm. ashless filter paper and wash 5 times with hot water. Ignite the paper and contents in the same crucible at a high temperature. Cool and weigh. The loss in weight is tungstic acid.

$$\frac{\text{WO}_3 \times 0.7931 \times 100}{2.336} = \% \text{ W}$$

II. The $\text{HCl-HNO}_3\text{-Cinchonine-Na}_2\text{CO}_3$ Fusion Method—This method differs from the preceding mainly in the use of cinchonine, the purpose of which is to precipitate all the tungsten. A blank determination should be made on each lot of chemicals, especially the sodium carbonate.

Special Solution Required—Dissolve 25 g. of cinchonine in 200 ml. of dilute HCl (1:1). For a wash solution dilute 30 ml. of this solution to 1000 ml. with hot water.

Procedure—For 10% W, or more, weigh a 2 g. sample; for less than 10% W, weigh a 4 g. sample; for less than 1% W, use a separate sample for silicon. Dissolve in 100 ml. of HCl, keeping volume at 100 ml. by additions of water. Oxidize with HNO₃ (5-10 ml.) dropwise, until the solution is completely oxidized. Evaporate to dryness, and bake. If only W is required, evaporate to a paste, take up in dilute HCl and again evaporate to a paste. Take the residue up in 60 ml. of HCl (1:1), digesting until the soluble portion dissolves. Then add 2 drops HNO₃. Add 100 ml. of hot water, 5 ml. of the cinchonine solution, and boil a few minutes until the WO₃ is clean and yellow. After the WO₃ has settled, filter through a No. 42 Whatman paper. Put ¼ of a paper (11 cm.) that has been macerated in hot water, in the apex of the filter. Wash with hot HCl (1:4), which contains 10 ml. of cinchonine solution per l. Wash once with hot water. If any WO₃ adheres to the beaker, wipe it off with a small piece of paper moistened with NH₄OH, and then add this to the main WO₃ precipitate. Transfer to a platinum crucible. Ignite the WO₃ precipitate at a dull red at first, and finally at a full red heat. Weigh. Weight equals crucible + WO₃ + SiO₂ + impurities. Cover the residue with HF. Add 2 drops concentrated H₂SO₄. Evaporate slowly to dryness until all white fumes are driven off. Ignite at a full red heat as before. Weigh. Weight lost is SiO₂. Calculate the silicon, thus:

$$\frac{\text{Wt. SiO}_2 \times 0.4672 \times 100}{\text{Wt. of Sample}} = \% \text{ Si}$$

Gross weight now equals crucible + tungsten + impurities. Add to the crucible sodium or sodium-potassium carbonate equal to about 10 times the weight of the residue. Use only carbonate that gives no blank. Fuse completely and dissolve fusion in 100 ml. of hot water. Filter through a No. 42 Whatman paper, and wash with hot water. Ignite and weigh. In the absence of Mo the weight now is crucible + impurities, and the difference between these last two weights is the pure WO₃.

$$\frac{\text{WO}_3 \times 0.7931 \times 100}{\text{Wt. of Sample}} = \% \text{ W}$$

In the presence of molybdenum, treat the filtrate from the sodium carbonate fusion as for molybdenum in the presence of tungsten, determine the former as MoO₃, and subtract this weight from the weight of the WO₃.

III. The Perchloric Acid-Cinchonine-NaOH Solution Method.

Special Solutions Required—See Method II above.

Procedure—Transfer the sample, 2.336 g. if W is under 3%, and 1.168 g. if it is over, to a 400 ml. beaker and dissolve in 60 ml. of 1:1 HCl. When solution is completed, add HNO₃ dropwise until iron is oxidized, boil for a few minutes and add 25 ml. of HClO₄ (70%). Evaporate to fumes of perchloric acid and continue fuming for 2 or 3 min. Cool, add 150 ml. of H₂O and 25 ml. of HCl (1:1) and bring to boil. Add 5 ml. of cinchonine solution and digest for 30 min. or longer at 90-95°C.

Filter on a tight ashless paper, washing well with cinchonine wash solution. Dissolve the small amount of W which cannot be scrubbed from the beaker with a little NH₄OH and evaporate to dryness. After bringing into solution with 1:1 HCl add a few drops of cinchonine solution, bring to a boil and pour through filter. Transfer filter to a weighed platinum crucible and ignite at as low a temperature as possible until carbon is gone. Cool and weigh as SiO₂ + impure WO₃. Treat with 2 drops H₂SO₄ (1:1) and 3-5 ml. of HF. Evaporate carefully to dryness on a sand bath, ignite at 750-850°C., cool and weigh again as impure WO₃.

Dissolve the impure WO₃ in the crucible with 15 ml. of a 10% solution of NaOH, transfer to a small beaker, and dilute with H₂O to 75 ml. Filter on a small ashless paper, wash well with hot water and reserve filtrate. Dissolve oxides from paper into beaker, with hot 1:1 HCl. Precipitate with NH₄OH, boil, and refilter, washing well with hot H₂O. Ignite and weigh the residue, the weight of which must be subtracted from the weight of impure WO₃. If molybdenum is present or suspected, determine it as MoO₃ in the filtrate and deduct its weight from the weight of WO₃.

The difference between the weight of SiO₂ + impure WO₃ and the weight of impure WO₃, multiplied by 40 represents the percentage of Si if 1.168 g. sample was

used. If 2.336 g. sample was taken, multiply difference in weight by 20 to obtain per cent Si.

The difference between the weight of crucible and the corrected weight of WO_3 multiplied by the factor $0.679 \times 100 = \% \text{ W}$, if a 1.168 g. sample is used. For a 2.336 g. sample, the factor is 0.3395.

Determination of Tungsten in High Speed Steels—Transfer 1 g. of drillings to a covered 250 ml. beaker, add 50 ml. of HCl and heat to incipient boiling. Place the beaker on a warm spot and add a few drops of HNO_3 , and wait until the vigorous action subsides. The addition of HNO_3 results in the momentary formation of brown ferric compounds which are quickly reduced again with the production of unstable dark green compounds. When this change takes place, repeat the treatment with HNO_3 until it ceases to recur. In this way the whole of the iron is oxidized with the production of a perfect solution of it and the tungsten and with the use of very little more HNO_3 than is required for the oxidation of the iron only. Evaporate the liquid as quickly as possible until tungstic oxide begins to separate and then add 10 ml. of cinchonine solution, afterwards boiling more slowly until 20 ml. is reached. Add then 100 ml. of hot water and set aside for at least 15 min.

Filter through paper pulp, wash with 5% HCl and water; dry and ignite in a platinum crucible; remove the silica with HF alone, ignite again and weigh. Cover the residue with about twice its weight of dry sodium carbonate and place the crucible in the hottest part of the muffle for 5 min. When the fused mass is cold, extract with hot water and filter. Ignite the washed residue in the same crucible. In the absence of molybdenum the loss in weight is tungstic oxide.

$\text{Weight of } \text{WO}_3 \times 0.7931 \times 100 = \% \text{ tungsten.}$

If the steel contains molybdenum, treat the filtrate from the sodium carbonate fusion as directed for molybdenum in the presence of tungsten (p. 702), determine the molybdenum as MoO_3 , and deduct this weight from the weight of WO_3 .

Determination of Copper—Copper is determined by several methods known as the CuS gravimetric method, the CuS electrolytic method, the CuS -iodide-thiosulphate method, the thiosulphate-KCN method, and the thiocyanate-iodate method. All give satisfactory results, but the first and the last only can be described here in detail. These two methods can be carried out in the ordinary laboratory, and no elements interfere when analyses are made with variations as noted.

I. CuS Gravimetric Method—(a). *Procedure for All Steels Except Tungsten Steels*—Transfer 5 or 10 g., according to the copper content, to an 800 ml. beaker, add 200 ml. of dilute H_2SO_4 (1:9), and heat gently. When solution is complete dilute to 500 ml., heat to boiling and saturate with H_2S for 30 min., as the solution cools. Digest 30 min., add paper pulp, filter and wash 3 times with dilute H_2SO_4 (1:99) saturated with H_2S .

(b). *For Tungsten Steels*—Dissolve 10 g. in 100 ml. of dilute HCl (1:1). Add 25 ml. of HNO_3 (1:1) and boil gently until precipitate is a bright yellow. Dilute to 150 ml. with hot water, digest 5 min., filter and wash with dilute HCl (1:9). Add 15 ml. of H_2SO_4 to the filtrate and evaporate to fumes. Cool, add 100 ml. of water, and, if necessary, filter and wash with dilute H_2SO_4 (1:20). To the clear filtrate add 5 g. of tartaric acid, neutralize with NH_4OH , add 5% by volume of H_2SO_4 . Heat just to boiling and pass H_2S for 15 min. Let the precipitate settle, then filter and wash as in (a).

Transfer the paper containing the copper sulphide precipitate, which may also contain some MoS_3 , to a 30 ml., tall form porcelain crucible, and ignite at 550°C . Fuse with 2-4 g. of an alkali-pyrosulphate. Dissolve melt in 25 ml. of dilute HCl (1:9), dilute to 100 ml., neutralize with 5% NaOH solution and add 0.3 ml. in excess. Boil 3 min. digest 20-30 min., filter and wash with 0.5% NaOH solution, discard the filtrate or reserve for molybdenum. Dissolve precipitate in 15-25 ml. of hot dilute HNO_3 (1:3), wash with hot water, add 5 ml. of H_2SO_4 and evaporate to fumes. Cool, dilute to 40 ml., add an excess of NH_4OH and heat to boiling. Allow precipitate to settle, filter, and wash with hot water. If precipitate is considerable in amount repeat by dissolving in hot dilute HNO_3 and again adding NH_4OH . Neutralize the filtrate or filtrates with dilute H_2SO_4 (1:1), add 4 ml. in excess and adjust volume to 100 ml. Heat to boiling and keep saturated with H_2S for 20 min. Filter and wash as in (a). Transfer filtrate to a weighed porcelain or quartz crucible. Ignite carefully to 900°C . Cool over a good desiccant and weigh as CuO . $79.89 \times$ the weight of CuO divided by weight of sample used gives the per cent Cu.

II. The Electrolytic Method—Transfer the ammoniacal solution to a 250 ml. electrolytic beaker. Neutralize with H_2SO_4 (1:1), add an excess of 8 ml. and 4 ml. of HNO_3 (1:1), weigh cathode and electrolyze 12 hr. with 0.5 ampere. Wash cathode with water, dip in alcohol, dry 1 min. at 100°C ., and weigh. Increase in weight $\times 100$ divided by weight of sample gives the per cent copper.

III. The KI-Thiosulphate Method—Dissolve ignited oxide in 5 ml. of HNO_3 . Warm and transfer to a 200 ml. beaker with 25 ml. of H_2O . Boil, add excess of bromine water and boil off. Add slight excess of dilute NH_4OH , boil to a faint odor, add 3 ml. of glacial acetic acid, boil 1 min., cool quickly and dilute to 100 ml. Add 6 ml. of 50% KI solution, and titrate at once with standard thiosulphate (3.9 g. per l., 3 days old, checked against a standard steel). When the brown color fades add 3 ml. of fresh starch solution, and titrate to disappearance of the blue color. Calculate per cent copper. One ml. of the sodium thiosulphate solution equals 0.001 g. of copper.

IV. Thiocyanate-Iodate Method—Solutions Required.

Starch Solution—Fresh, see under Sulphur.

Thiocyanate—Dissolve 50 g. of KCNS in 1000 ml. of H_2O .

Standard Iodate—Dissolve in order 2 g. of KOH and 20 g. of KIO_3 in 2000 ml. of H_2O and standardize against standard thiosulphate.

Standard Thiosulphate—Dissolve 68.75 g. of $\text{Na}_2\text{SO}_3 \cdot 5\text{H}_2\text{O}$ in 1000 ml. of H_2O . Standardize against Bureau of Standards sodium oxalate through KMnO_4 .

Procedure—Transfer 5 g. to a 750 ml. flask, and treat as follows:

(a). **Carbon and Low Alloy Steels**—Dissolve in 85 ml. of H_2SO_4 - HNO_3 mixture (167 ml. of H_2SO_4 and 666 ml. of 1.20 HNO_3 diluted to 1 l.) or 75 ml. of H_2SO_4 (1:10), hot. Dilute to 300 ml., add $(\text{NH}_4)_2\text{S}_2\text{O}_8$ until MnO_2 precipitates, boil 15 min. and reduce by adding 70 ml. of 25% sodium sulphite solution or 30 ml. of stannous chloride solution (250 g. of SnCl_2 , 500 ml. of HCl , 500 ml. of H_2O).

(b). **High Chromium Nickel Steels**—Dissolve in 50 ml. of a mixture of HCl and HNO_3 (equal parts), add 20 ml. of HClO_4 and 2 ml. of HF , evaporate and fume 10 min. under cover. Cool, dilute to 100 ml., boil 1 min., filter and wash with hot H_2O . Add NH_4OH until $\text{Fe}(\text{OH})_3$ persists after stirring. Add 10 ml. of H_2SO_4 (1:1), dilute to 300 ml., heat to boiling and reduce as in (a).

(c). **Tungsten Steels**—Dissolve with 50 ml. of HCl . Add slowly 15 ml. of HNO_3 (1:1) and boil until tungstic acid is a bright yellow. Dilute to 100 ml., digest 10 min., filter and wash with HCl (1:10). Add 10 ml. of H_2SO_4 to filtrate, evaporate, and fume 1 min. Add 400 ml. of H_2O , warm until salts dissolve, and reduce as in (a).

To the reduced solution add 25 ml. of thiocyanate solution, boil 5 min., and let stand 5 min. Filter on a close paper, wash flask and filter 10 times with cold 2% H_2SO_4 . Transfer filter and precipitate to flask, add 20 ml. of HCl (1:1), and 4 ml. of standard iodate for each 0.1% copper. Macerate paper thoroughly, dilute to 500 ml., and add 1 ml. of 10% KI solution for each ml. of iodate. Add standard thiosulphate slowly with stirring until iodine color fades. Add 5 ml. of starch solution, and continue titrating until the blue color disappears. If the thiosulphate is less than $\frac{1}{2}$ of the iodate, repeat the determination with more iodate. The difference between the iodate and thiosulphate represents iodate required to oxidize the cuprous thiocyanate, and each ml. of the latter equals 0.05% copper.

Determination of Chromium—(Silicon, Vanadium and Tungsten)—All the methods for chromium in steel are volumetric and differ only in the reagents used to oxidize the chromium and in the details of titrating the chromic acid with a ferrous sulphate solution. Under certain conditions silicon and tungsten or vanadium, or all three, may be determined on the same sample as the chromium, though in referee or special work results for each should be checked by another method.

Special Solutions Required (All Methods).

Standard Ferrous Ammonium Sulphate—0.1 Normal (Use in All Methods)—To make a 0.1 N solution transfer 39.114 g. of $\text{FeSO}_4(\text{NH}_4)_2 \cdot \text{SO}_4 \cdot 6\text{H}_2\text{O}$ to a 1000 ml. flask containing about 500 ml. of H_2O , add 100 ml. of dilute H_2SO_4 (1:1), shake until dissolved, and dilute to 1 l. The solution is oxidized slowly by exposure to the air, hence 40 g. per l. is generally used, unless provision can be made for storing the solution under pure hydrogen or nitrogen. This solution is best suited for titrating 30-100 mg. of chromium. For low chromium (under 3%) use half, and for high

chromium (over 10%) use twice as much of the salt, or one-tenth as much for chromium under 0.10%. If the solution is not stored under H_2 or N_2 , standardize every day it is used by titrating with the standard oxidant, preferably using blanks containing all the reagents treated as in a regular determination.

Standard Oxidant Solutions—Potassium Permanganate—Except when the end point is obtained potentiometrically, the chromic acid is reduced by adding a slight excess of the ferrous ammonium sulphate solution, which is then back titrated with a suitable oxidant, usually potassium permanganate. Potassium dichromate or ceric sulphate can be used in conjunction with suitable internal indicators. If the former is used, it must be purified and taken as the primary standard or standardized through permanganate against sodium oxalate. If ceric sulphate is used, it can be standardized against sodium oxalate direct by adding an excess and back titrating with ferrous ammonium sulphate solution, using ortho-phenanthroline ferrous ion (2 drops of 0.025 molar solution) as indicator. However, potassium permanganate standardized against Bureau of Standards sodium oxalate is still used almost universally, and is therefore selected as the standard. Usually a tenth normal solution is most convenient to use, though a slightly stronger solution may be employed for high chromium, and for minute amounts (under 0.01%) a 0.02 *N* solution is desirable. In any case the method of preparing the solution is the same, and will be described only for the 0.1 *N* solution.

Standard 0.1 Normal Potassium Permanganate—A 0.1 *N* solution requires 3.1606 g. of $KMnO_4$. In preparing the solution, however, about 3.2 g. are used, as the $KMnO_4$ is not absolutely pure and some is decomposed in making up the solution. For the same reasons it is well to prepare a dilute solution at the same time as the stronger solution to use in adjusting the concentration of the latter.

Dissolve the $KMnO_4$ in about 900 ml. of cold water and let age one week, or in hot water and let age 24 hr. Filter through a purified asbestos pad and dilute the stronger solution to 1 l. with the dilute solution. Standardize against Bureau of Standards sodium oxalate according to directions supplied with the sample and adjust strength by adding a calculated amount of the dilute solution. One ml. of 0.1 *N* solution is equal to 0.001734 g. of chromium, from which factor percentages may be calculated after proper corrections for blank, provided the chromium is all oxidized to chromic acid or H_2CrO_4 .

The standardization of the solutions should be checked by analysis of a standard sample of steel of approximately the same composition as the steels to be analyzed.

Weight of Sample—In all methods the weight of sample is varied according to the per cent of chromium likely to be present, about as follows:

For chromium under 0.5% use 5 g. sample.
For chromium between 0.5% and 1% use 3 g. sample
For chromium between 1% and 5% use 2 g. sample.
For chromium between 5% and 12% use 1 g. sample.
For chromium between 12% and 25% use 0.5 g. sample.

Perchloric Acid Method—The sample is brought into solution in various ways. If the steel dissolves readily in perchloric acid, transfer the sample to a 400 ml. beaker, and add 10 ml. of water and 20 ml. of perchloric acid (70%), adding an additional 10 ml. of the acid for each g. of sample in excess of 1 g. Cover, heat gently till sample is dissolved, then boil and heat at fuming temperature for 10 min. Cool somewhat, add 10 mg. of $KMnO_4$ crystals, cool rapidly, add 50-60 ml. of water and 0.5 ml. of HCl , and boil 3 min. Cool rapidly, dilute to about 300 ml. and titrate as directed below.

If desired vanadium may be estimated by treating as directed for vanadium and silicon by filtering and treating in the usual way.

For steels attacked by nitric acid, transfer the sample to a 400 ml. beaker and dissolve in 40-60 ml. of dilute nitric acid (sp.gr. 1.20), varying the acid according to the size of the sample. Then add 20 ml. of perchloric acid (70%) and 10 ml. additional for each g. of steel used, and proceed as directed above.

For steels not attacked by nitric acid, use HCl or a mixture of HCl (2 parts) and HNO_3 (1 part) with 20 ml. of water to dissolve the sample. Then add perchloric acid and proceed as directed above.

For stainless steels, and other high alloy steels, particularly those containing tungsten, transfer the sample (0.5 or 1 g.) to a 500 ml. flask, add 10-15 ml. of a mixture consisting of 1 volume of perchloric acid (70%) and 2 volumes of phos-

phoric acid (85%), and digest at 180°C. for 5 min. under a loosely fitting cover. Add to the clear green solution 15 ml. of a mixture of 1 volume of perchloric acid and 2 volumes of 80% sulphuric acid, and raise the temperature to 205°C. for 10 min. To the orange colored solution add 10-15 mg. of KMnO_4 crystals, swirl, and plunge intermittently into ice cold water to cool as rapidly as possible, then add 70 ml. of cold water, follow with 0.5 ml. of HCl and boil 5 min. Cool rapidly, dilute to 300 ml. with cold water, and titrate as directed below.

Persulphate Method—Transfer the sample to a 600 ml. beaker and dissolve in 50 ml. of dilute H_2SO_4 (1:4) or in 60 ml. of mixed acids (160 ml. of H_2SO_4 , 80 ml. of H_3PO_4 , and 760 ml. of H_2O). If tungsten is present and it is desired to determine chromium potentiometrically, omit H_3PO_4 . Heat until action ceases, add 5 ml. of HNO_3 , and boil free of nitrous fumes. If carbides persist or tungsten is present, evaporate to first separation of salts, dilute with 50 ml. of water, add 10 ml. of HNO_3 and again evaporate. Add 200 ml. of H_2O , filter and wash with water. To the filtrate add 20 ml. of a 1% solution of AgNO_3 , heat to boiling and add slowly while stirring a concentrated solution of ammonium persulphate until a permanent pink color develops. Boil 5 min., add slowly 5 ml. of dilute HCl (1:1) and continue boiling until the pink or brown color disappears, adding 2-3 ml. more HCl if necessary. Boil 10-15 min. longer, cool to room temperature, dilute to about 300 ml. with cold water and titrate as directed below.

Potassium Permanganate Method—Transfer the sample to a 400 ml. beaker, and dissolve in 50-120 ml. of dilute H_2SO_4 (1:5). Heat gently until action ceases, oxidize by adding HNO_3 dropwise, then add 20 ml. in excess. If tungsten is present digest (under cover) until the tungstic acid is a light yellow color, and boil 10 min. If much tungsten is present, dilute to 250 ml. with hot water, filter, and wash with hot water. Heat the filtrate to boiling and add dropwise a saturated solution of KMnO_4 until the solution is a deep pink color or a permanent precipitate forms. Cover and boil 20 min. Filter through a close filter of purified asbestos, wash well with cold 5% H_2SO_4 solution, dilute to 300 ml. and titrate as directed below.

Potassium Chlorate Method—Dissolve the sample with 50 ml. of dilute HNO_3 (sp.gr. 1.20) in a 600 ml. Erlenmeyer flask. Heat until residue, if any, is a light yellow color and free of black particles. If solution is slow, add HCl a few drops at a time to avoid an excess until solution is complete. Evaporate until a slight scum of ferric nitrate begins to form. Add 125 ml. of HNO_3 , and heat to boiling. Remove from the heat and add 3-4 g. of KClO_3 . Boil vigorously to a volume of about 50 ml. Cool, add 100 ml. of cold water, filter through a purified asbestos pad, and wash with cold water until the washings are colorless. Discard the precipitate of MnO_2 and WO_3 . Dilute the filtrate to 300 ml. and titrate as directed below.

Bicarbonate Separation for Low Chromium and Vanadium—Transfer the sample (5 g. or 10 g.) to a 500 ml. Erlenmeyer flask, cover, and dissolve with 60 ml. of H_2SO_4 (1:9). Add 140 ml. of boiling water. Add at once an 8% solution of sodium bicarbonate (about 36 ml.) until a permanent precipitate forms, and then add 4 ml. in excess. Boil 1 min. Filter through an 11 cm. paper and wash 3 times with hot water. Transfer filter to a 400 ml. beaker. Wash flask with 50 ml. of mixed acids used in the persulphate method above, and transfer to the beaker containing the paper. Add 5 ml. of HNO_3 , boil free of brown fumes, and filter through an asbestos mat. Wash filter with hot water, dilute to 200 ml. and oxidize chromium, as described under the persulphate method. Titrate with 0.02 *N* solutions as directed below.

Visual Titration of the Chromium and Vanadium—To the cold solution obtained by any of the preceding methods, add from a burette a slight excess (2 ml. or more) of standard ferrous ammonium sulphate solution. If enough is present, 1 drop will give an intense blue color when added to 1 drop of fresh $\text{K}_3\text{Fe}(\text{CN})_6$ solution. While stirring, titrate the excess with standard potassium permanganate solution until a faint pink end point is obtained which persists after stirring for 1 min. To correct the titration for dilution effect and color interference, boil the solution for 10 min., cool, dilute to original volume and titrate to the same end point as before. The number of ml. of KMnO_4 solution used in the first titration, minus the number used in the blank gives the ml. used in titrating the excess ferrous sulphate. This difference subtracted from the ml. of KMnO_4 solution equivalent to the total ml. of ferrous sulphate solution used gives the number of ml. of KMnO_4 solution equivalent to the chromium present. To find the per cent chromium, multiply this quan-

tity by 100 times the chromium factor for the permanganate and divide by the weight of sample used.

To determine vanadium, add 5 ml. of H_3PO_4 if not already present, and then 15-30 ml. of 0.03 *N* ferrous ammonium sulphate or equivalent. (Test for excess as when titrating chromium, 1 ml. of 0.03 *N* solution = 0.0015 g. of V.) Stir, add 8 ml. of 15% $(\text{NH}_4)_2\text{S}_2\text{O}_8$ solution, stir 1 min., and titrate with 0.03 *N* KMnO_4 solution to the same end point as before. Subtract the KMnO_4 used from that equivalent to the ferrous sulphate used, and convert the difference to per cent vanadium.

Potentiometric Titration of Chromium—Absence of Vanadium and Tungsten—In this method the chromium is titrated direct with ferrous ammonium sulphate solution, which is standardized against pure $\text{K}_2\text{Cr}_2\text{O}_7$ by the same method of titration. Vanadium, if present, is titrated as chromium, and tungsten held in solution with H_3PO_4 makes the end point hard to detect. Two types of potentiometric apparatus are available, namely; the Larabee and the Kelly, the latter being the older and the one in more general use. With the Kelly apparatus, the solution is usually prepared by the persulphate method, and the procedure is as follows:

Place the beaker containing the solution in position, and adjust apparatus to bring the needle or beam of light near the left end of the scale. Add the standard ferrous sulphate solution slowly until the indicator moves to the right and remains in this position. If the end point is overrun add standard potassium dichromate solution till the indicator moves back to the left, then the ferrous sulphate solution until 1 drop causes the indicator to move permanently to the right. Multiply the ml. of ferrous ammonium sulphate actually used in reducing the chromic acid by its chromium value times 100 and divide by the weight of sample used to find the per cent chromium.

Determination of Vanadium—Potentiometric Titration—Applicable to chromium-tungsten-vanadium steels.

Apparatus—These directions are written for the Kelly electrometric apparatus. Before titrating, flush out the calomel cell tube, so as to insure the purity of the electrolyte in the cell. The calomel cell contains a bottom layer of Hg, then a layer of Hg_2Cl_2 , and is then filled with a neutral solution of *N* KCl (74.55 g. per l). The other electrode is a platinum tipped wire, which makes contact with the external circuit.

Special Solutions Required—Standard Potassium Dichromate Solution—Dissolve 0.9626 g. of $\text{K}_2\text{Cr}_2\text{O}_7$ in H_2O and dilute to exactly 1000 ml. The $\text{K}_2\text{Cr}_2\text{O}_7$ should be recrystallized and either heated just to the fusion point or dried at 200°C . This solution should be renewed at least once a week. One ml. is equal to 0.1% of vanadium in 1 g. sample.

Standard Ferrous Ammonium Sulphate Solution—Dissolve 8 g. of $\text{FeSO}_4(\text{NH}_4)_2 \cdot \text{SO}_4 \cdot 6\text{H}_2\text{O}$ in 1000 ml. of H_2O containing 50 ml. of H_2SO_4 . The factor showing the relation of ferrous sulphate and potassium dichromate should be obtained each day by titrating a 30 ml. portion of the chromate solution.

To compensate for losses due to occlusion and incomplete oxidation, which may amount to as much as 0.02% vanadium, and also compensate other possible errors, it is well to check this solution against a standard steel of approximately the same composition as the steels to be analyzed.

Procedure—Dissolve 2 g. of sample in 100 ml. of dilute H_2SO_4 (1:4). When solution is complete, gradually add dropwise 10 ml. of HNO_3 (1:1). Boil until tungsten, if present, is completely oxidized to yellow tungstic oxide. Dilute to 200 ml. with hot H_2O , add 40 ml. of HNO_3 and boil for 1 hr. at such a rate that the final volume will be between 100 ml. and 125 ml. Longer boiling does no harm, provided the volume of the solution does not fall below 100 ml. Cool, dilute to 300 ml. with ice water and see that the temperature of the solution is $5-10^\circ\text{C}$. Titrate with the FeSO_4 solution as follows:

Lock the beaker containing the solution into position. Turn on the switch that controls the motor and release the galvanometer needle. Next press downward and make a half-turn clockwise on the 2 plunger switches on the front of the box. Then turn the knob that controls the resistance, so as to cause the galvanometer needle to come to rest at zero. Finally, add from the burette the ferrous ammonium sulphate solution, until the change in potential causes the needle to move to, and remain at the right extremity of the dial. Read the burette and calculate the percentage of vanadium.

Unless the operator is an expert it is best to back titrate with the standard

dichromate solution, as follows: Add a slight excess of the ferrous ammonium sulphate, and then add the standard dichromate solution slowly until the indicator (needle or light) returns to its original position. Finally, add the ferrous solution drop by drop to the first large movement of the indicator, which is taken as the end point. Multiply the volume of ferrous solution by its bichromate equivalent. Subtract the volume of dichromate used, multiply by 0.1, and divide by the number of g. in the sample and by 0.995 to find the per cent vanadium. The factor 0.995 compensates for the vanadium not oxidized by the nitric acid.

Umpire Method¹—Briefly this method is carried out as follows: Dissolve the sample (2 g. if V is over 0.1%, 5 g. if under 0.1%) in dilute H_2SO_4 (1:10) and make a bicarbonate separation. (See under manganese and chromium.) From this point carry a blank through all steps also. Transfer paper and precipitate to the original flask and dissolve in 20 ml. of HNO_3 and 5 ml. of H_2SO_4 by heating to fumes, adding HNO_3 if necessary to destroy all carbonaceous matter. Then expel HNO_3 , dilute to 40 ml., filter off tungstic acid, if present, and evaporate to 40 ml., neutralize with NH_4OH , add H_2SO_4 equal to 1% of the solution, and separate vanadium by electrolyzing in a mercury cathode cell (preferably Melaven type). When all iron has been removed from the solution (ferricyanide test), draw off the liquid, washing the mercury 3 times with H_2O . Add 1 ml. of H_2SO_4 , heat to 75°C ., and add KMnO_4 solution to a decided pink. Heat to boiling, pass SO_2 gas for 5 min., and drive out excess SO_2 with a current of CO_2 , or until escaping gas has no effect upon a very dilute solution of KMnO_4 . Cool the solution to 70°C . and titrate to first pink with 0.03 N KMnO_4 solution. Repeat reduction with SO_2 and titrate as before. Titrate the blank to the same end point and subtract. Multiply the corrected volume of permanganate used by its vanadium titer times 100 and divide by the g. of sample used to find the per cent vanadium.

Vanadium in High Chromium Steels—Direct Titration After Volatilizing the Chromium—Procedure—For vanadium up to 1%, use 2 g. of sample and 1 g. for higher percentages. Transfer the sample to a 250-ml. Erlenmeyer flask. For 2 g. add 10 ml. HCl and 50 ml. HClO_4 (58-60%). Heat to dissolve and fume to complete oxidation of the chromium. Cool somewhat and volatilize the chromium with NaCl or HCl as described under manganese, persulphate method. Transfer to a 400-ml. beaker, dilute to 200 ml., and stir in 5 ml. of orthophosphoric acid (85%). Add an excess of ferrous ammonium sulphate solution and oxidize the excess by adding 8 ml. of a 15% solution of ammonium persulphate. Titrate the solution with standard KMnO_4 solution to a faint pink end point persistent for 1 minute. Correct this volume for the blank, if required for accuracy, and multiply the difference by 100 times the vanadium titer of the permanganate solution and divide by the weight of sample used to find the per cent vanadium.

Determination of Nickel

I. Dimethylglyoxime Method—Special Solutions Required

Ammoniacal Dimethylglyoxime Solution—Dissolve 10 g. of dimethylglyoxime in 650 ml. of NH_4OH and dilute to 1 liter. Make up fresh every week. Recommended where large amounts must be used.

Alcoholic Dimethylglyoxime Solution—Dissolve 10 g. in 1000 ml. of ethyl alcohol (95%). Keeps indefinitely.

Weight of Sample—Use 0.25 g. for nickel over 8%; 0.5 g. for 3-8%; 1 g. for 1-3%; 2 g. for 0.1-1%, and 5 g. for less than 0.1% nickel.

Procedure—Transfer the sample to a 400 ml. beaker and dissolve with 30 ml. of HCl , if possible, or with dilute H_2SO_4 (1:1), dilute HNO_3 (sp.gr. 1.135), or mixtures of these. If none of these acids are effective, add dilute HNO_3 and 10 to 15 ml. of HClO_4 (60%). If HNO_3 is not used initially, heat the solution almost to boiling and add 10 ml., dropwise. Boil and evaporate to moist dryness. Add 30 ml. of HCl and boil to 15 ml. Dilute with 40-50 ml. of water and filter immediately. Wash with HCl (1:1) and hot water. Discard the filter and residue of silica and tungstic acid. In the absence of cobalt dilute to 150 ml.; if cobalt is present, add in addition 100 ml. of water for each 1%. Add 60 ml. of a 20% solution of tartaric or citric acid, and 15 ml. additional for each additional g. of sample, if more than 1 g. was used. Neutralize with ammonia, add 1 ml. excess, and acidify slightly with acetic acid. In

¹See Chemical Analysis of Iron and Steel by G. E. F. Lundell, J. I. Hoffman, and H. A. Bright, John Wiley and Sons, New York.

the absence of cobalt, heat to 70°C. and add 10 ml. of glyoxime solution, plus 5 ml. additional for each 0.01 g. of nickel present. While stirring add ammonia until slightly alkaline, and let stand in a warm place for not less than 15 min., and preferably for 1 hr. For low nickel let the solution stand 8-12 hr. If cobalt is present add the dimethylglyoxime in the cold, and let stand for at least 4 hr. If the precipitate does not have the characteristic red color, or if manganese is high (over 1%) dissolve with a hot solution of 20 ml. of HCl (1:1) and 5 ml. of HNO₃, wash, dilute to 300 ml., add 10 ml. of tartaric or citric acid solution and reprecipitate as before.

After settling proceed by either of the following methods:

(a). Filter on a weighed, close, glass frit crucible filter, keeping the crucible full of liquid, and wash with hot water to which 1 drop of ammonia has been added. Dry at 110-120°C. and weigh as NiC₂H₃O₄N₄, of which 20.32% is nickel.

(b). Filter through a paper, wash thoroughly with hot water, and transfer to a weighed crucible. Cover with another wet paper, heat gradually until the paper is charred, and ignite to constant weight at a dull red temperature. Weigh as NiO, of which 78.58% is nickel.

II. Silver-Nitrate Cyanide Titration Method—Not applicable to steels containing copper, cobalt or tungsten.

Solutions Required—*Citric-Sulphuric Acid*—Dissolve 400 g. of citric acid crystals in water, add 160 ml. of concentrated H₂SO₄ and dilute to 1000 ml. with water.

Potassium Iodide—Dissolve 50 g. in 100 ml. of water.

Standard Silver Nitrate Solution—Dissolve 5.789 g. of AgNO₃ in water and dilute to 1 l. One ml. is equivalent to 0.001 g. of Ni.

Standard Potassium Cyanide Solution—Dissolve 5 g. of KCN in water and add 5 g. of KOH to preserve the solution. Dilute to 1000 ml. with water. Standardize as directed below.

Procedure—Dissolve 1 g. of sample in 20 ml. of concentrated HCl. Oxidize with 10 ml. of HNO₃ (sp.gr. 1.13). Boil off fumes and evaporate to 15 ml. If silicon is high dissolve in 20 ml. of concentrated HCl and 2 ml. of HF. Evaporate to dryness and bake. Take up with HCl and oxidize with HNO₃ as directed above. Cool, add 50 ml. of the citric-sulphuric acid solution and dilute to 250 ml. Then add NH₄OH until the solution is just alkaline to litmus paper. Cool and add dropwise with constant stirring enough NH₄OH to give a distinct odor of ammonia. This excess of ammonia is important. Too little will give high results, too much will give low results. Add 1 ml. of the KI solution and stir. Then add exactly 5 ml. of the standard AgNO₃ solution from a burette. A pale yellow cloud of AgI will form. Titrate with the standard KCN solution, while stirring constantly, until the solution just becomes clear. Finally, titrate back with the standard AgNO₃ until a faint but distinct cloud of AgI is again formed. Calculate the total ml. of AgNO₃ used to ml. of KCN. Subtract this from the total ml. of KCN used. This difference, multiplied by the value of the KCN in terms of nickel gives the percentage of nickel in the sample.

Caution—The KCN changes with age. Hence, the theoretical titer is based on the AgNO₃, and the solutions must be compared daily as follows: Treat a nickel steel standard free of cobalt as directed above. Add the nickel equivalent of the AgNO₃ used to the nickel value of the standard, and divide the sum by the ml. of cyanide solution used to find the nickel value of 1 ml. of the cyanide.

Slight modifications in the procedure as outlined above permit titration and determination of the nickel photometrically. The exact procedure will depend somewhat upon the type of photometric apparatus employed.

III. Color Method—Applicable only to steels containing less than 0.10% nickel.

Procedure—Transfer 1.2 g. of drillings to a 400-ml. Erlenmeyer flask and dissolve in 60 ml. HNO₃ (1.13 sp. gr.). When nearly in solution add 15 ml. ammonium persulphate solution (22.5%) to destroy carbides, and cool as soon as the persulphate is decomposed.

Add a little water to cool somewhat, then add 20 ml. of NH₄OH and 3 ml. of 1% KCN solution. Mix by whirling the flask, and add 15 ml. of NH₄OH. Dilute to exactly 300 ml. in a volumetric flask, immediately filter off 50 ml. of the solution and transfer it to a 150-ml. Erlenmeyer flask.

To this solution add 3 ml. of a nearly saturated solution of dimethylglyoxime; whirl and add 5 ml. of sodium hypochlorite. Mix well and allow color to develop for several minutes. Transfer to a colorimeter or comparing tubes and determine the per cent nickel by comparison with a standard prepared as follows:

The Standard for Comparison—Add a measured amount of the standard nickel solution to a 50 ml. graduate and dilute to 50 ml. with water, adding 3 ml. of glyoxime and 5 ml. of sodium hypochlorite solution.

The Standard Nickel Solution—Mix 2550 ml. H_2O , 850 ml. HNO_3 , and add 1050 ml. NH_4OH . Add 1.9 g. KCN dissolved in 100 ml. H_2O , then 100 ml. of a solution of nickelous nitrate containing 0.336 of nickelous nitrate. Immediately add 850 ml. NH_4OH and dilute the whole to 17,000 ml.

One ml. of this solution is equivalent to 0.002% nickel when compared with a 1.2-g. sample of the unknown solution.

Determination of Molybdenum—Molybdenum may be determined gravimetrically, volumetrically, or colorimetrically. In the absence of interfering elements, the last method does not require a preliminary separation of the molybdenum, but is applicable only to steels containing small amounts. Hence, only the first two methods are used in the analysis of complex steels, and both involve a separation of molybdenum as sulphide. For molybdenum under 1%, the alpha-benzoinnoxime method as developed by H. B. Knowles¹¹ is used.

The following procedure is applicable to the largest number of the different types of steel.

Weight of Sample—The weight of sample used is varied from 1-5 g. according to the probable percentage of molybdenum present, to give 20-30 mg. of molybdenum.

Procedure—In the absence of tungsten transfer the sample to a 600 ml. beaker or flask and dissolve in 100 ml. of dilute H_2SO_4 (1:5) by heating gently until action ceases. Add 20 ml. of a 25% solution of ammonium persulphate and boil for 8-10 min.

In the presence of tungsten, dissolve the sample in 100 ml. of dilute HCl (1:1) and oxidize by adding HNO_3 dropwise, or by adding 20 ml. of dilute HNO_3 (1:1). Boil gently until the tungstic acid becomes a bright yellow, then either dilute to 150 ml. or evaporate just to dryness, take up in 10 ml. of HCl and add 50 ml. of water. Heat to boiling, filter and wash residue with dilute HCl (1:9). Reserve the residue. At this point some prefer to add 15 ml. of H_2SO_4 to the filtrate, evaporate to fumes, take up in 100 ml. of H_2O and filter off any additional residue on a small filter, which is washed with 1% H_2SO_4 , this precipitate being combined with the previous one. If the original solution was evaporated just to dryness, this step may not be necessary.

To recover molybdenum from the residue, fuse with sodium carbonate and take up in water and filter, or dissolve the residue on the filter with hot 5% solution of NaOH. In either case wash the paper with hot water, and once or twice with a little dilute H_2SO_4 . Add 5 g. of tartaric acid to the filtrate or solution, then neutralize with HCl or H_2SO_4 , adding an excess of 3 ml. of the former or 5 ml. of the latter. Heat to boiling and pass H_2S for 10 min. Filter, wash with dilute acid (1%) saturated with H_2S and reserve to add to the main portion of the molybdenum sulphide obtained as directed below.

The solution containing the bulk of the molybdenum may be treated by either of the following procedures:

(a). Add 5 g. of tartaric acid, neutralize with ammonia, make just acid with H_2SO_4 , and add 5 ml. excess for each 100 ml. of solution. Heat to boiling, pass H_2S for 30 min., dilute with an equal volume of hot water, continue to pass gas for 5 min. and digest at 60°C. for 1 hr.

(b). To the oxidized solution add ammonia until a slight precipitate of $Fe(OH)_3$ persists. Dissolve with a few drops of concentrated HCl and add 3 ml. excess. Bring the solution to a boil and pass H_2S gas through it. If the H_2S produces a deep red color, add more HCl, not over 1 ml. at a time, until the precipitate settles out readily. If the solution is too acid, the H_2S will not completely precipitate the molybdenum and the filtrate will be colored blue. In this case start the determination anew.

Separate the precipitate of sulphur and molybdenum sulphide by filtering through a close paper and wash with 1% H_2SO_4 or HCl saturated with H_2S .

If there is any doubt about the completeness of the precipitation of the molybdenum, boil to expel H_2S and reduce the volume to about 300 ml. Add 20 ml. of persulphate solution, boil for 10 min. and again pass H_2S for 15 min. Filter and wash as before. Transfer precipitates to a silica or porcelain crucible and ignite slowly and carefully to constant weight at a temperature not over 525°C. Complete the determination by either of the following methods:

(a). To the crucible add 10 ml. of HCl (1:1) and digest until dissolved. Wash

into a beaker and dilute to 50 ml. with H₂O. Boil. Now add a 5% solution of NaOH, until there are 2 drops in excess, using either litmus paper or phenolphthalein indicator. Filter, wash with hot water, burn off as before in the same crucible, cool, and weigh. Subtract the weight of impurities from the first weigh, and calculate difference to per cent Mo, using the factor Mo:MoO₃ = 0.667.

(b). Leach in 30 ml. of NaOH (4% sol.) for 30 min. on warm part of hot plate. Filter (suction, paper pulp) and wash free of NaOH, using phenolphthalein as indicator. Acidify with acetic acid, heat to the boiling point, and add sufficient lead acetate (4% sol.) to completely precipitate the molybdenum. Filter, preferably by suction, using paper pulp, and wash well with hot water. Burn off the paper slowly in front of the muffle (max. temp. 600°C.) and weigh as lead molybdate.

$$\frac{\text{PbMoO}_4 \times 0.2616 \times 100}{\text{weight of sample}} = \% \text{ Mo}$$

(c). *Presence of Arsenic, Vanadium, and Tin—Volumetric Method*—Destroy paper and oxidize the sulphide by digesting with HNO₃ and H₂SO₄ (5 ml.) until the solution is clear and light colored. Evaporate and fume to expel all HNO₃. Cool, dilute to 50 ml., add 0.01 g. of Fe₂(SO₄)₃, then NH₄OH until first appearance of reddish tint dispelled by stirring, and heat the yellow solution to boiling. Heat 75 ml. dilute NH₄OH nearly to boiling in a 250 ml. beaker, and pour the solution into it, stirring constantly. Add paper pulp, filter, wash with hot water, and reserve the filtrate. Dissolve the precipitate with hot H₂SO₄ (1:4), using as little acid as possible, then nearly neutralize, pour into NH₄OH, filter into reserved filtrate and wash with hot water as before. Neutralize the combined filtrates with dilute H₂SO₄ (1:1) and add an excess of 5 ml. for each 100 ml. of solution. Heat to boiling, add KMnO₄ solution until decidedly pink, and pass through a Jones reductor, collecting the reduced solution beneath a solution of ferric sulphate (0.1-0.2 g.) and phosphoric acid (5 ml.). Titrate with 0.03 N KMnO₄ solution, subtract blank, and calculate to per cent molybdenum. One ml. of 0.03 N KMnO₄ solution = 0.00096 g. of Mo.

Alpha-Benzoinoxime Method—Absence of Tungsten—Transfer 1 to 3 g. of sample to a 600-ml. beaker and dissolve in 50 ml. of H₂SO₄ (1:16). Heat and add HNO₃ dropwise to the decomposition of carbides and the oxidation of iron and molybdenum. To remove SiO₂, add a few drops of HF, and then 10 ml. of boric acid solution (4%). Boil, filter, if necessary, dilute to 100 ml., and reduce with FeSO₄ (about 0.5 g.) at room temperature. Cool to 5°C. and add 10 ml. of 2% alpha-benzoinoxime in ethyl alcohol, and 5 ml. additional for each 0.01 g. Mo present. While stirring, add bromine water to tint the solution, then add 5 ml. more of the alpha-benzoinoxime solution. Cool the beaker for 10 minutes longer stirring occasionally, add paper pulp, and filter rapidly. Refilter any of the first filtrate that may not be clear. Wash with 200 ml. of a cold, freshly prepared mixture containing 10 ml. of the alpha-benzoinoxime solution and 2 ml. of H₂SO₄. Transfer to a platinum crucible, cautiously dry, char the paper, and finally ignite to constant weight at 500-525°C. Digest with 5 ml. of NH₄OH, filter, wash with 1% NH₄OH, and ignite in the original crucible. Subtract the second weight from the first to find the weight of MoO₃, which multiplied by 0.667 gives the weight of Mo in the sample. To find per cent Mo, multiply the weight by 100 and divide by the weight of sample used.

Determination of Cobalt—There are several methods for the determination of cobalt. One of the methods recommended is that of Hoffman, in which the major portion of the iron is separated with ether, while the remaining iron and the copper are separated with cupferron, and the cobalt finally precipitated with alpha nitroso-beta-naphthol. However, the following method is still generally used for high alloy steels, such as high speed steel. The method is based on separation of cobalt from Fe, Cr, W, and V, with zinc oxide and the subsequent precipitation of the cobalt with alpha nitroso-beta-naphthol in HCl solution, in which nickel remains soluble. The procedure is as follows:

Procedure—Weigh 2 g. of the sample into a 400 ml. beaker, dissolve in 50 ml. of concentrated hydrochloric acid and boil to the absence of fumes. When solution is complete, oxidize the iron with about 10 ml. of concentrated nitric acid and boil to the absence of fumes. Cool the solution and add ammonia slowly while stirring until the precipitate of iron hydroxide formed dissolves with difficulty. Cool to room temperature and wash into a 500 ml. volumetric flask. Add slowly, with constant agitation of the flask, an emulsion of zinc oxide until an excess is present. As this point is approached the solution becomes milky and a slight amount in

excess produces a heavy voluminous brown precipitate. Dilute to the mark with water and empty into a 600 ml. beaker. Mix thoroughly by stirring. Let the precipitate settle and decant 250 ml. of the solution through a dry 12.5 cm. filter paper into a 250 ml. volumetric flask. When 250 ml., representing 1 g., have been filtered, this solution is transferred to a 400 ml. beaker and 5 ml. of concentrated hydrochloric acid are added. The solution is heated to near the boiling point, and the cobalt precipitated with alpha nitroso-beta-naphthol. Just before the solution is ready to precipitate dissolve 2 g. of alpha nitroso-beta-naphthol in 25 ml. of concentrated acetic acid. Heat the reagent gently and add it to the hot hydrochloric acid solution containing the cobalt. The cobalt is precipitated as a red compound. A portion of the excess reagent also precipitates. Two g. of alpha nitroso-beta-naphthol will precipitate 0.05 g. or 5.0% cobalt. If the percentage of cobalt is low, use a correspondingly smaller amount of the reagent.

Hold near the boiling point for 15 min., let settle and filter on an 11 cm. ashless filter paper, using paper pulp. The last portion of the precipitate and reagent is removed from the sides of the beaker with difficulty. Wash the precipitate 5 times alternately with hot dilute hydrochloric acid (1:1) and hot water and finally 5 times with hot water. If accuracy is not a requirement in the work, ignite in a weighted silica or porcelain crucible at a low temperature until the paper is gone, then at a high temperature for 30 min. Cool and weigh. The increase in weight is cobalt oxide, Co_3O_4 , contaminated with a small amount of iron.

Therefore, in accurate work purify the precipitate before or after igniting as follows: Transfer the precipitate to a 250-ml. beaker and dissolve it in a mixture of 15 ml. HCl and 5 ml. HNO_3 , boiling the solution down to a volume of 5 ml. Note the color of the concentrated solution, which will be of an intense green if 1 or 2 mg. of cobalt are present. To eliminate every trace of HNO_3 , add 25 ml. of HCl , and repeat the evaporation. Dilute the solution to 50 ml. and add dilute ammonia (1:1) dropwise to the precipitation of the small amount of iron. Dissolve the precipitate by adding 1 or 2 drops of dilute HCl (1:1), and reprecipitate by adding 1 or 2 ml. of a 50% solution of ammonium acetate and boiling. Filter and wash with 10 ml. of a hot faintly ammoniacal solution of ammonium acetate. Redissolve and repeat the precipitation. Wash as before, ignite, weigh, and subtract this weight from the weight of impure Co_3O_4 .

Weight of purified cobalt oxide, $\text{Co}_3\text{O}_4 \times 0.7343 \times 100 = \% \text{ cobalt}$.

The ignited oxide does not have the exact formula Co_3O_4 . If the weight of oxide is appreciable, it is, therefore, advisable to change the oxide to metallic cobalt by repeated ignition in hydrogen in a Rose-form crucible until the weight is constant.

Determination of Titanium—Titanium is determined by several different methods. The following is applicable to high chromium steels such as the stainless steels, and other alloy steels, containing no vanadium or tungsten.

Cupferron Method—Absence of W and V—In the absence of copper, transfer 0.5-1 g. to a 200 ml. beaker and add 100 ml. of 10% H_2SO_4 and heat until all action appears to have ceased. Cool the solution to 10°C ., add a little ashless paper pulp, and precipitate the titanium by adding dropwise a freshly prepared 6% solution of cupferron (ammonium nitrosophenylhydroxylamine, $\text{C}_6\text{H}_5(\text{NO})\text{ONH}_2$), stirring constantly until the precipitate assumes a reddish brown color. Fill the tip of an 11 cm. filter paper with paper pulp, filter the solution and wash filter and precipitate 10-12 times with cold 5% H_2SO_4 . Transfer the filter and precipitate to a 50 ml. platinum crucible and ignite at a temperature no higher than sufficient to destroy the carbon of the filter paper. Cool and add to the crucible about 1 g. of potassium pyrosulphate, fuse gently and dissolve the melt in 50 ml. of dilute H_2SO_4 (1:4). Cool the solution to room temperature and determine titanium colorimetrically as directed below.

In the presence of much copper, dissolve sample as above, then filter on a 9 cm. paper containing some ashless paper pulp, and wash paper and residue well with 10% H_2SO_4 . Cool the filtrate to 10°C . and precipitate with cupferron as directed above. Transfer the filter paper containing the residue insoluble in H_2SO_4 to the original beaker. Add 25 ml. of dilute HNO_3 (sp.gr. 1.135) and heat gently to dissolve copper. Add about 50 ml. of hot H_2O , neutralize with ammonia, add a slight excess, and heat to boiling. Filter and wash well with hot H_2O . Ignite the paper and residue at a low temperature just sufficient to burn off the carbon and add the ignited residue to the ignited cupferron precipitate, then fuse the combined

residues with potassium pyrosulphate, dissolve in dilute H_2SO_4 (1:4) and determine titanium as directed below.

Transfer the solution, which should not contain more than 0.005 g. of titanium (0.5% on a 1 g. sample, or 1% on a 0.5 g. sample) to a color comparison tube. Add 5 ml. of 3% hydrogen peroxide ("dioxygen") and mix thoroughly. To another comparison tube add 45 ml. of cold 10% H_2SO_4 , 5 ml. of the same hydrogen peroxide solution, and then add from an accurate burette measured amounts of standard titanium sulphate solution (1 ml. = 0.0005 g. of Ti), mixing after each addition, until the color of the standard is slightly less intense than the solution. Dilute the standard to the same volume as the unknown and mix. After preliminary comparison add titanium sulphate solution to the standard, adding, at the same time, an equal volume of 10% H_2SO_4 solution to the unknown, and mixing after each addition, until the colors match exactly. To find the per cent titanium in the sample, multiply the number of ml. of standard titanium sulphate solution used by 0.05 and divide by the weight of sample taken.

Procedure for High Titanium—Over 1%—Treat 1 g. of the sample for the separation of titanium with cupferron as directed above. Ignite the precipitate in a 100 ml. platinum dish at a temperature just sufficient to burn the paper completely. Cool, add 15 ml. of dilute H_2SO_4 (1:1), and 10 ml. of hydrofluoric acid (48%), then evaporate in an air bath to fumes. Rinse down the wall of the dish with cold water and again evaporate to fumes to expel any trace of HF. Add 50 ml. of water and filter if a residue remains. Wash with hot water and reserve the filtrate. Ignite the residue at low temperature in a platinum crucible and fuse with a little potassium pyrosulphate. Take up in dilute H_2SO_4 (1:4), add a slight excess of ammonia, and heat to boiling. Filter, if there is a precipitate, and wash with hot water. Dissolve the precipitate with a little hot dilute H_2SO_4 and add to the reserved filtrate.

Add to the solution containing all the titanium 1 g. of tartaric acid, make slightly ammoniacal, neutralize with dilute H_2SO_4 and add an excess of 2 ml. of the concentrated acid for each 100 ml. of solution. Saturate the solution with H_2S and separate any precipitate by filtering and washing thoroughly with H_2S water containing about 1% of H_2SO_4 and 1% of tartaric acid. Discard the precipitate. Now add to the solution ammonium hydroxide until there is an excess of 2 ml. and pass H_2S for 5 min. Stir in some ashless paper pulp and filter. Wash the precipitate well with ammonium sulphide containing about 1% ammonium tartrate and discard. Boil the filtrate to the complete expulsion of H_2S . Adjust the volume of the solution to 150 ml. and add 30 ml. of dilute H_2SO_4 (1:1). Cool to 10°C ., add some paper pulp, and precipitate titanium with cupferron as directed above, adding the cupferron until there is an excess as indicated by the formation of a snow white precipitate which rapidly disappears. Filter, wash 12-15 times with cold 5% H_2SO_4 , and then 5 times with 5% ammonium hydroxide. Transfer the paper and precipitate to a platinum crucible and gradually ignite to between 1050 and 1100°C . Cool in a desiccator and weigh. Multiply the weight of the TiO_2 thus found by 59.95 and divide by the weight of sample taken to find the percentage of titanium.

To check the results fuse with potassium pyrosulphate, take up in dilute H_2SO_4 (6%), and proceed by one of the following methods:

(a) Pass the solution through a Jones reductor into a solution of ferric sulphate and phosphoric acid, and titrate with 0.05 N KMnO_4 solution. Make a blank determination in the same way and correct. One ml. of 0.05 N KMnO_4 = 0.002395 g. of Ti. The presence of Fe, Cb, Cr, Mo, U, V, W, or nitrates gives high results.

(b) Aliquot the solution and determine titanium in a suitable portion colorimetrically. If results do not check, test for other elements such as zirconium and correct the titanium gravimetric result.

Determination of Total Aluminum—Aluminum is determined in various ways, usually as the oxide or the phosphate, or by titrating the quinolate, and the procedure up to the final precipitation must be modified not only for different kinds and types of steels, but also according to the final precipitation. When the final precipitation is to be made with 8-hydroxyquinoline, the procedure of Bright and Fowler¹⁰ is recommended, though many prefer to make the preliminary separations in other ways than with sodium bicarbonate and sodium hydroxide. For example, the following is recommended for steels containing high percentages of nickel and aluminum:

Dissolve 0.5 g. or 1 g. of the sample, according to the aluminum present, with dilute HCl (1:1). Filter, wash with water, ignite, and reserve the residue. Oxidize the filtrate with HNO_3 , evaporate, add HClO_4 , and continue the evaporation to fumes, adding a ml. of HF from time to time as required to volatilize all the silica. Dilute to 200 ml., add ammonia until the solution is almost neutral, and electrolyze over a mercury cathode until the solution is free of iron. In the meantime volatilize the silica in the reserved residue, ignite gently, fuse with acid sodium sulphate, dissolve, and add to the electrolyzed solution. Precipitate the aluminum in the combined solutions with 8-hydroxyquinoline, and determine the aluminum either gravimetrically or volumetrically as directed by Bright and Fowler.

The best of the older and more tedious methods are given below, the first being applicable to carbon and alloy steels containing Al, Cr, V, Mo, and Ni, and the second to any aluminum bearing steel, including those containing tungsten. Neither method is designed for the determination of small percentages, such as of Al and Al_2O_3 in carbon steels.

Ether-Carbonate-Sodium Peroxide Separations Followed by Precipitation with Ammonia—Dissolve 2 g. sample in 50 ml. of HCl (1:1). Oxidize with 10 ml. of concentrated HNO_3 and evaporate to a paste. Add 5 ml. of concentrated HCl, and again evaporate to a paste. Take up with 5 ml. of concentrated HCl, and rinse wall of beaker with 20 ml. of water. Transfer the solution to a separatory funnel, using not more than 10 ml. of water to rinse the beaker. In a separate room or in a space remote from open flames or anything heated to redness or to a glowing temperature add 50 ml. of ether to the funnel. Cool and shake well, keeping the solution cold. Let settle 1 min. Draw off into another separatory funnel the bottom or acid layer, which contains the Al, Cr, V, Ni, most of the P, and a little of the Fe. Discard the top or ether layer. To this second separatory funnel add 50 ml. of ether, cool, shake and cool as before. Draw off the bottom layer into a 400 ml. beaker. Avoiding open flames, evaporate the dissolved ether under a well-ventilated hood, then evaporate to a paste. Take up with 5 ml. of HCl (1:1), oxidize with 1 ml. of HNO_3 and dilute with cold water to 200 ml. Add Na_2CO_3 , until the solution is near the neutral point. Then neutralize with Na_2O_2 and add 3 g. in excess. Add 5 g. more of Na_2CO_3 , boil for 2 min., and let settle. Filter into an 800 ml. beaker, washing with a hot 5% solution of Na_2CO_3 . Dissolve the precipitate in 10 ml. of HCl. Dilute to 100 ml. with water. Again add Na_2O_2 , filter and wash as before. Combine the filtrates, which now contain the Al and Cr. To this filtrate add dilute HCl (1:1) cautiously until a cloudiness appears. Heat to the boiling point, and add HCl (1:4), until a drop of the solution shows a brown ring on "Instantaneous" tumeric paper, after 2 seconds. Add a little paper pulp and let the precipitate settle. Filter and wash with hot 5% NH_4NO_3 solution. To the filtrate add ammonia until alkaline to methyl red, boil, filter and wash to recover any $\text{Al}(\text{OH})_3$ not precipitated. Dissolve the precipitate on both papers with 15 ml. of hot HCl (1:1). Add 10 ml. of perchloric acid, evaporate to fumes and fume 10 min. Cool and add 50 ml. of cold water. Filter and wash with hot water containing a little HCl, keeping the volume under 100 ml. To the solution, add 3 drops excess NH_4OH . Heat to boiling and let precipitate settle. Filter and wash well with hot 5% NH_4NO_3 . Ignite carefully in a weighed platinum crucible, using a low flame until the paper is all burned. Then cover and ignite for 5 min. or to a constant weight at 1000°C . or higher. Weigh as Al_2O_3 , 52.914% of which is aluminum. Divide product by 2 to find per cent Al.

Bicarbonate and Sodium Hydroxide Separations Followed by Precipitation of Al as Hydrate or Phosphate—The sample is dissolved in dilute H_2SO_4 (1:9), and both the weight of sample and amount of acid used are varied according to the probable percentage of aluminum present. The acid used equals 10 ml., plus 10 ml. additional for each g. of sample. Thus, for carbon steels and alloy steels containing very little aluminum, 10 g. are dissolved in 110 ml. of the acid, while 2 g. is used for aluminum steels containing up to 1%, and solution is effected with 30 ml. of acid. To compensate for errors due to reagents and glassware, it is well to start a blank using ferrous ammonium sulphate equivalent to 2 g. of Fe, and dissolve in a minimum amount of H_2O containing 10 ml. of the acid.

Procedure—Transfer the sample to a 500 ml. Erlenmeyer flask, add the acid, cover, and heat gently. Nearly all of any arsenic present should escape as AsH_3 . When action ceases add 200 ml. of boiling H_2O , and heat to boiling. Add 8% solution of NaHCO_3 from a burette until a faint precipitate appears, then add 4

ml. more. Let settle, filter and wash rapidly with hot H_2O , discarding the filtrate, unless desired for Mn.

The insoluble matter on the filter paper contains all the Al, Cr, Ti, and Zr in the steel, and may contain in addition all the Ce, Cu, P, Sn, U, V, and W contaminated with more or less ferric iron, and Co, Ni, and Si, if present.

In the absence of tungsten and much chromium or vanadium, dissolve the precipitate with 20 ml. of hot HCl (1:8) and wash paper with hot H_2O , collecting solution and washings in a 400 ml. beaker. Ignite the paper at low temperature in an open porcelain crucible, brush into a platinum crucible, fuse with $K_2S_2O_8$ or $NaHSO_4$, and dissolve the melt in the reserved solution.

In the presence of tungsten or much chromium or vanadium, sluice the bicarbonate precipitate into a beaker. Reserve paper and dissolve precipitate in 5-15 ml. of HCl and oxidize carbides and tungsten by adding 5-7 ml. of HNO_3 dropwise to the hot solution. If a yellow residue remains indicating tungsten, dilute, filter, and wash with hot H_2O , reserving the filtrate. Transfer paper to a beaker, dissolve the tungstic acid with a minimum of NH_4OH , boil to expel excess, dilute, macerate paper, filter, wash with hot water and discard the filtrate. Place all the filter papers in a platinum crucible, ignite just until paper is burned, fuse with $K_2S_2O_8$, and dissolve the melt in the reserved filtrate.

Note: If preferred, the Fe and Mo and a part of the As, P, and Sn may be separated by an ether extraction as in the preceding method, and the filtrates containing the Al and Cr treated as directed below.

To the tungsten-free acid solution add SO_2 water (2 ml. or more) and boil to reduce any chromic acid, then add HNO_3 (2 or 3 ml.) and boil to oxidize iron. Add NaOH solution to the first appearance of the slightest precipitate, then pour into 80 ml. of a 5% solution of NaOH, stirring constantly. Boil 5 min., settle, filter and wash with 1% NaOH. If aluminum is high, dissolve the precipitate with HCl, reprecipitate with NaOH, and combine the filtrates. Discard the precipitate, which contains the Fe, Cr, Cu, Ti, and Zr or use for determining Cr, Ti, or Zr and treat the filtrate, which contains the Al, P, V, and part or all of any tin present, as follows:

Neutralize the filtrate or filtrates with HCl, add 5 ml. in excess, and evaporate to 250 ml., when the precipitate that forms on adding HCl should have been dissolved. Unless tin is known to be absent, pass H_2S into the hot solution, filter and wash with H_2S water containing a few drops of HCl. Discard any precipitate, boil the filtrate to expel H_2S , and determine Al by either of the following methods; the first being preferable only in the absence of vanadium and in steels of low phosphorus content.

(a) Add 3 or 4 drops of methyl red indicator solution, then dilute ammonia slowly, with constant stirring, until the color changes from red to yellow. Boil 1 min. If the color changes to red, add ammonia until it changes to yellow again, boil 30 sec., let settle, filter and wash with hot water. If Al is high, redissolve with HCl, add paper pulp and reprecipitate as before. Ignite both filters at low temperature in a weighed platinum crucible. Moisten with dilute H_2SO_4 , add 3 or 4 ml. of HF, evaporate and ignite to constant weight at $1000^\circ C$. or higher. Record this weight less any blank found as $Al_2O_3 + P_2O_5 + V_2O_5$. Fuse with $NaHSO_4$ or $K_2S_2O_8$, dissolve melt in H_2O , and divide into two equal parts. Determine P in one part, vanadium in the other, multiply results by 2, calculate to P_2O_5 and V_2O_5 , and subtract the sum from the impure Al_2O_3 . Multiply this difference by 52.914 and divide by the weight of sample to find the per cent Al in the steel.

(b) To the acid solution from the H_2S separation of Sn, add 0.5 g. $(NH_4)_2HPO_4$, 2 or 3 drops of methyl red indicator, ammonia until the solution is distinctly yellow, and dilute HCl (1:20) until it just turns red again. Add paper pulp, heat to boiling and add 20 ml. of a 20% solution of ammonium acetate. Boil 5 min., let settle (10 min.-2 hr.), filter and wash free of chlorides with hot 5% NH_4NO_3 . If vanadium is high, dissolve with HCl, dilute to 250 ml. and reprecipitate. Ignite the precipitate gradually to constant weight at $1000^\circ C$., and weigh as $AlPO_4$. Subtract any blank found, multiply by 22.11 and divide by the weight of sample used to find the per cent Al.

Determination of Selenium—Selenium may be determined with fair accuracy in several ways, but the following are generally used by the manufacturers of steels containing selenium. The procedure, with permissible variations, is as follows:

Transfer 5-10 g. of the sample to a 600 ml. Erlenmeyer flask or a covered 400 ml. beaker. Add 50-60 ml. of a mixture of equal parts of concentrated HCl and HNO₃. If the initial reaction is violent, cool in running water. When solution is complete treat by either of the following methods:

(a) Add 35 ml. of perchloric acid (70%) and evaporate rapidly until red chromic acid crystals separate or until perchloric acid vapors begin to condense near the top of the beaker or flask. Cool slowly, cautiously add 100 ml. of cold water, and agitate until separated salts are dissolved. To remove silica, cool, filter through a close paper, and wash with warm dilute HCl (1:1) and warm water to a volume between 150 and 175 ml. Add HCl equal to 70% of the solution, follow with 100 ml. of H₂O freshly saturated with SO₂, warm to 65°C. and allow to stand 3 hr. at this temperature. Cool to below 10°C., and separate the selenium as directed below.

(b) Evaporate the mixed acid solution to dryness on a water bath. Do not bake. Add 10 ml. of HCl (1:1) and 20 ml. of cold water, stir, and digest on the water bath till salts have dissolved. Filter through a close paper, wash 2 or 3 times with dilute HCl (1:1) and finally with water until free of chlorides. Discard the residue and dilute filtrate and washings to about 150 ml. with cold water. Add concentrated HCl equal to 70% of the volume of the solution (about 100 ml.) and pass a current of washed SO₂ gas through the solution at the rate of about 2 small bubbles per sec., holding the temperature at 20-25°C. (room temperature) and stirring frequently to granulate the selenium. After all the selenium has been precipitated and the solution saturated with SO₂, allow the precipitate to settle for 1 hr., then filter as directed below.

As a filter for collecting and weighing the selenium, prepare a Gooch crucible with thoroughly purified and washed asbestos of the amphibole variety, which has been dried and ignited at a temperature of 700°C., or higher. After the filter has been prepared, dry, ignite at 700°C, cool and weigh. Wash with water, dry at 90°C., and reweigh to check loss on ignition. Filter the solution containing the selenium through the crucible, washing the selenium upon the filter with warm dilute HCl (1:1). Then wash free of acid with warm water, 2 or 3 times with ethyl alcohol (95%), and once with ether. Dry the crucible in an air bath at 85-90°C. and weigh. Record the gain in weight as "impure selenium." To check the purity, ignite to constant weight at a temperature no higher than necessary to volatilize Se (690°C.), cool and weigh. If this weight is within 1 mg. of the ignited weight of the empty crucible, and the asbestos mat shows no marked discoloration, consider the selenium pure. Otherwise subtract the ignited weight of the crucible after volatilizing the selenium and record the difference as pure selenium. Divide the weight of pure selenium by the weight of sample taken to find the per cent selenium.

Determination of Columbium and Tantalum—The Umpire method recommended by the Bureau of Standards provides for the determination of columbium, tantalum, titanium and zirconium on the same sample. For details of this method, see "Chemical Analysis of Iron and Steel," by Lundell, Hoffman and Bright, John Wiley and Sons, New York. Most manufacturers of steels alloyed with these elements use the method of T. R. Cunningham which, with some minor modifications introduced by others, is carried out as follows:

Procedure—Transfer 2 g. to a 400 ml. beaker, treat with 30 ml. of HCl at 60-70°C., and, when all action has ceased, evaporate to a paste (approximately 15 ml.). Add 200 ml. of warm water (some prefer a 5% solution of HCl), stir, add 30 ml. of freshly prepared H₂SO₄, and boil 10 min. Without delay, stir in a little ashless paper pulp, and filter through an 11 cm. paper carrying a light bedding of the pulp. Wash 12-15 times with warm dilute HCl (1:20) and discard filtrate and washings.

Transfer the filter and residue to a 50 ml. platinum crucible, and ignite gradually to a dull red until the paper is completely burned. Add 5-10 ml. of perchloric acid (60%) and 10-15 ml. of hydrofluoric acid (48%), evaporate the HF in an air bath and finally heat on a sand bath until copious fumes of perchloric acid are evolved. Rinse the wall of the crucible with 5 ml. of H₂O, and repeat evaporation and fuming to expel all the HF. Transfer the contents of the crucible to a 250 ml. beaker with 100 ml. of dilute HCl (1:20), add 20 ml. of the H₂SO₄ (saturated solution of SO₂), and boil 5-10 min. Filter and wash as before, transfer paper and residue to a weighed 50 ml. platinum crucible, heat gradually till the carbon is burned, and ignite to constant weight at 1000-1050°C., cooling in a desiccator. If the

residue is uniformly white in color and titanium is known to be absent, consider it $\text{Cb}_2\text{O}_5 + \text{Ta}_2\text{O}_5$, and treat for the titration of columbium as described below. If the residue is discolored, fuse with 1-2 g. of $\text{K}_2\text{S}_2\text{O}_7$, dissolve the melt in 100 ml. of dilute HCl (1:20), and repeat the hydrolysis with H_2SO_4 , filter, ignite and weigh as before. Weigh as $\text{Cb}_2\text{O}_5 + \text{Ta}_2\text{O}_5$ (+ TiO_2 if titanium is present).

Fuse the mixed oxides with 15 times their weight of $\text{K}_2\text{S}_2\text{O}_7$. When the fusion is clear, cool somewhat, add 5 ml. of H_2SO_4 (sp.gr. 1.84), and heat on a hot plate until complete solution is effected. Transfer the solution to a dry 250 ml. beaker, and rinse the crucible with 15 ml. of H_2SO_4 . Add 1 g. of succinic acid, then 10 ml. of a saturated solution of succinic acid, stir and dilute to 100 ml. If titanium is absent, 10 ml. of H_2SO_4 may be added to the crucible, which is rinsed with 30 ml. of the acid, and the whole diluted to 200 ml.

Unless titanium is known to be absent, add an excess of KMnO_4 solution (2.5%) and 5 ml. of a 3% solution of H_2O_2 . If a straw to amber color develops, determine titanium colorimetrically, reserving all the solution. In the positive absence of titanium, this step is omitted.

The columbium in the solution is determined as follows: Prepare a Jones reductor with a zinc column at least 15 in. long. Wash 20-mesh zinc with water, then with dilute (2%) H_2SO_4 , and amalgamate for 30-40 seconds by immersion in 0.5% solution of mercuric chloride. This zinc is good for 5-10 determinations. Transfer the amalgamated zinc to the reductor, wash thoroughly with water, once with 10% sulphuric acid, and keep zinc covered with water. Mount the reductor in a 1 l. suction flask containing 25 ml. of ferric sulphate-phosphoric acid mixture (100 g. $\text{Fe}_2(\text{SO}_4)_3 + 150$ ml. of 85% H_3PO_4 per l.), so that the tip of the reductor is immersed in the mixture, and arrange to apply gentle suction as required.

Heat 150 ml. of a 20% solution of sulphuric acid to 70°C ., and the solution containing the columbium to 60°C . Open the stopcocks and, without allowing the zinc at the top of the reductor to go dry at any time, pass in succession 100 ml. of the warm 20% H_2SO_4 solution, the solution containing the columbium, 50 ml. of the warm dilute acid, and 100 ml. of hot water, closing the stopcock with the water just covering the top of the zinc. Without delay transfer the solution in the suction flask to an 800 ml. beaker, and titrate with 0.05 N KMnO_4 , which has been standardized against Bureau of Standards sodium oxalate. Now run a blank through the reductor and titrate in the same way, substituting 100 ml. (or 200 ml.) of 20% H_2SO_4 solution for the solution containing the columbium. Subtract this blank from the KMnO_4 solution used to titrate Cb and Ti and calculate the per cent Cb and the per cent Ta in the sample as follows:

1 ml. of 0.05 N KMnO_4 = 0.002333 g. of Cb , or 0.002395 g. of Ti .

Divide the weight of titanium found in the color test by 0.002395 to find the equivalent ml. of KMnO_4 solution and subtract to find the ml. of KMnO_4 used in titrating the columbium. Multiply this difference by 0.002333 to find the weight of columbium in the sample, which multiplied by 100 and divided by 2 (wt. of sample) gives the per cent columbium. Then multiply the weight of columbium by 1.4296 to find the equivalent weight of Cb_2O_5 , and the weight of any titanium by 1.668 to find the TiO_2 . Subtract the sum of these products from the weight of the mixed oxides to find the weight of Ta_2O_5 in the sample. Finally, multiply the weight of Ta_2O_5 by 81.94 and divide by 2 to find the per cent Ta in the sample.

Determination of Tin—Tin in steel is determined either volumetrically or gravimetrically, the former being generally restricted to routine or control analyses of steels in production. More refined methods are available but not practicable for use in production.

Volumetric Method for Control Purposes—(Copper Absent or Low)—This method is not applicable to steels containing more than the usual amount of residual copper.

Special Solutions Required:

Potassium Iodate (0.1 N)—Dissolve 3.57 g. of KIO_3 and 20.0 g. of KI in 1 liter of water.

Starch Solution—Mix 1 g. of wheat starch with a little water and add to 100 ml. of boiling water. Boil 1 minute, cool, and decant the clearer liquid for use. Prepare a new solution every 3 to 5 days as required.

Potassium Iodide Solution, 10%—Dissolve 10 g. of KI in 100 ml. H_2O .

Standard Potassium Iodate Solution 0.01 N —Dissolve 0.357 g. of KIO_3 and 2.0 g. of KI in about 200 ml. of water, add 0.4 g. of KOH and dilute to 1000 ml.

The solution is standardized and the tin factor established by treating known solutions of pure tin with tin-free iron or steel as directed in the procedure below. Each ml. of this solution is equivalent to approximately 0.0058% tin on a 10 g. sample.

Procedure—Either take the HCl solution from an evolution sulphur determination or transfer 10 g. of the sample to a 500-ml. Florence flask, add 100 ml. of HCl, insert a funnel trap, and heat almost to boiling until solution is effected. In either case, start a blank using approximately the same volume of water and unneutralized acid. As soon as the cuttings have dissolved cool rapidly to room temperature and add 5 to 10 ml. of the 0.1 N potassium iodate solution, according to the per cent tin expected, adding 10 ml. for 0.1% tin or more and 5 ml. for tin under 0.1%. After 5 minutes, add 2.5 g. of aluminum in granular form (20 mesh). As soon as the aluminum has dissolved, heat to boiling and boil gently 20 minutes. Cool the solution rapidly, add 10 ml. of a 10% solution of KI, 5 ml. of the fresh starch solution, and titrate to a selected end point with the standard potassium iodate solution. From the number of ml. of the iodate solution used subtract the blank, and multiply the difference by the tin factor to find the per cent tin.

Gravimetric Method—This method is applicable to carbon steels either copper-free or containing copper and in addition all other elements ordinarily occurring as residuals in the steel.

Caution—Care must be observed to avoid heating any of the solutions obtained in the following procedure above 100°C.

Procedure—Dissolve 5 g. of the sample in 100 ml. of dilute HCl (1:1), heating gently to hasten solution. As soon as the cuttings have dissolved, add 5 g. of KClO₃, continue heating until the odor of chlorine has disappeared, add 50 ml. of H₂O, and maintain the temperature of the solution at 100°C. for 30 minutes. Filter, wash the filter and residue with hot water, dilute the filtrate to 400 ml., and pass a rapid stream of washed H₂S through the solution for 1 hr. Let the precipitate settle, preferably for 8 to 10 hr. Then filter and wash the filter and residue free of ferrous iron with H₂S water containing 1% HCl by volume. Transfer the filter and contents to a porcelain crucible and ignite at a low temperature until the paper is completely consumed. Brush the ignited residue into a 250-ml. beaker, add 50 ml. of a mixture of equal parts by volume of HCl and HNO₃, and heat gently for 1 hr. or longer. Dilute slightly, filter, and wash thoroughly with hot water. Transfer the filter and contents to a weighed platinum crucible, ignite at a low temperature, and weigh. Add 5 drops of H₂SO₄ and 5 ml. of HF. Evaporate to dryness on a sand bath or in an air bath, and slowly ignite to a temperature of 850–900°C. Cool, weigh, and compare with the weight before the HF-H₂SO₄ treatment. From the last weight subtract the weight of the crucible, and calculate the difference to per cent tin.

$$\frac{\text{Weight of residue} \times 0.7876}{3 \times 100} = \% \text{ tin in the sample.}$$

Determination of Zirconium—Transfer 2-5 g. of sample to a 250-ml. beaker, add 30 ml. of HCl + 15 ml. additional for each g. of sample, and heat gently until the cuttings have dissolved. Dilute to 150 ml., cool to 20°C., add slowly and with constant stirring 2 g. of cupferron dissolved in 35 ml. of cold water or sufficient to impart a reddish brown color to the precipitate. Add paper pulp, filter, and wash with cold dilute HCl (1:9). Ignite the residue and fuse with K₂S₂O₇. Dissolve in 100 ml. of dilute H₂SO₄ (1:9), filter, and wash with some of the same acid. Add 2 ml. of H₂O₂ (30%) to the filtrate and 25 ml. of an 8% solution of (NH₄)₂HPO₄. Stir and allow to stand several hours on a sand bath at about 65°C. Add paper pulp and filter, washing thoroughly with a 5% solution of (NH₄)₂NO₃. Transfer to a weighed platinum crucible, dry, char, and ignite at 1050°C. for 15 minutes. Cool and weigh as impure ZrP₂O₇. Fuse with K₂S₂O₇, dissolve in 40 ml. of dilute H₂SO₄ (1:9) containing 5 ml. of H₂O₂ (3%). If titanium is present determine it colorimetrically, calculate it to Ti₂P₂O₇, deduct from the weight of ZrP₂O₇, and calculate the difference to per cent zirconium.

Determination of Lead—Of the several ways for determining lead in steel, the sulphide-molybdate method is selected as one of the most rapid and simplest procedures of widest application. Neither molybdenum nor many of the other elements occurring in steel interfere. For the determination of lead in complex alloy steels, the procedure given below may have to be modified by introduction of other steps.

Procedure—For lead between 0.10 and 0.30%, dissolve 5 g. of the sample in

100 ml. of dilute hydrochloric acid (1:1) contained in a 600 ml. beaker. For lead under 0.10%, use 10 g., and for lead over 0.40%, 2 or 2.5 g.

Boil and rapidly evaporate until iron salts crystallize, but do not bake. Add 300 ml. of boiling water, stir until all the salts have dissolved, and pass a stream of hydrogen sulphide through the solution for at least 5 minutes, but preferably until the solution has cooled to room temperature. Filter and wash the beaker and precipitate once with 1% HCl solution saturated with H_2S .

Place a 250 ml. beaker under the funnel and dissolve the precipitate on the paper with warm dilute HCl (1:1). Moisten the paper once or twice with hot dilute nitric acid (sp. gr. 1.20) and wash four or five times with hot water. Dissolve 2 g. of tartaric acid in the acid solution of lead chloride, neutralize with ammonia and add an excess of 5 ml.

Heat the ammoniacal solution to boiling, and add 10 ml. of a 5% solution of ammonium molybdate. Permit the precipitate to settle, then collect it, preferably, upon a weighed close (No. 4) glass frit filtering tube or crucible. Wash the filter and precipitate free of soluble salts, dry at $130^{\circ}C$. to constant weight, cool to room temperature in the balance case, and weigh. Record the increase in weight of the filter as $PbMoO_4$.

If the $PbMoO_4$ is collected upon a paper filter, wash with hot water containing a little ammonium nitrate, dry, ignite gradually with free access of air to a temperature no higher than necessary to burn off the paper, and weigh at room temperature. Rapid ignition at a high temperature may reduce the salt and volatilize part of the lead and molybdenum.

Multiply the weight of $PbMoO_4$ by 56.43, and divide by the weight of sample used to find the per cent lead.

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Methods for the Determination of Oxygen, Nitrogen, and Hydrogen in Ferrous Materials*

General—The determination of oxygen, nitrogen, and hydrogen in ferrous materials is difficult, because the total amount to be determined is frequently a matter of only a few thousandths of one per cent by weight, and is further complicated by the variety of forms and combinations of the three gaseous elements that comprise the small total. Oxygen exists in steel chiefly as discrete particles (inclusions) consisting of oxides and silicates of iron, manganese, aluminum, and the alloying elements, the distribution of oxygen among these combinations varying with the composition of the steel and with the refining and deoxidation practice. Small amounts of oxygen also may exist in solid solution in the iron and in the form of gaseous compounds, chiefly CO, in small blow holes or fissures. Nitrogen occurs chiefly in the combined form (nitrides of the metallic elements) but small amounts may be present in solid solution and perhaps as elemental gas. Hydrogen seldom is present in amounts as great as 0.001% and it is not definitely known whether hydrogen exists in solid solution or combined as metallic hydrides.

In such a situation it is natural that the methods of analysis differ widely in basic principles and in intent. In the determination of oxygen, for example, some methods are intended for the isolation and separate determination of individual oxides whereas others yield a single value for total oxygen without attempting to determine its distribution among the various combinations that are present. Because of this diversity in aims and basic principles it has been difficult to establish the accuracy of the different methods. Attempts to do this by comparison of the results obtained from the same materials by different methods of analysis are of little value unless each method yields concordant results in the hands of different analysts, so that the results are representative of the method rather than of the technique and procedure of the individual analyst. The data of the recent co-operative study of methods for the determination of oxygen in steel¹ showed that most of the methods require further refinement and development in order that different analysts using the same method may obtain results in satisfactory agreement.

At the present time the choice of an analytical method, to use in attacking a problem of gases in metals, depends upon the item that is considered to be of most importance, whether it be the total gas content or the content of one or more of the individual compounds. Complete information regarding the total gas content and the distribution of this total among the various combinations is difficult to obtain and usually requires determinations by several methods of analysis.

Individual methods for the quantitative determination of oxygen, nitrogen and hydrogen in ferrous materials are described in the ensuing paragraphs. Methods that yield qualitative rather than quantitative data, for example microscopic and petrographic methods, are not included in this report.

Methods for the Determination of Oxygen and Oxides—Most of the work on the determination of oxygen and oxides has been concerned with samples of solid metal but some attempts have been made to determine the oxygen content of liquid steel. Herty² suggested killing a spoon sample of molten steel with an excess of metallic aluminum. Subsequent determination of Al_2O_3 in the solidified spoon sample furnishes a measure of the oxygen content of the liquid steel but sufficient data are not available to evaluate the accuracy of this method. Difficulty in sampling may be encountered because of segregation of the Al_2O_3 in the solidified spoon sample and it is difficult to avoid some oxidation of aluminum by oxygen from other sources than the oxides dissolved in the molten iron.

The determination of the amount and composition of the gases evolved during the solidification of molten steel also has received attention. In the method of Hare, Peterson, and Soler³ the sample of liquid metal is collected and allowed to solidify in an evacuated steel tube. Determinations of the oxygen evolved as CO during solidification of the sample were found to be in good agreement with determinations of oxygen by Herty's method. A similar procedure was described by Wüster and Piwowsky.⁴

Methods for the quantitative determination of oxygen and oxides in solid steel fall into two groups: (a) reduction methods and (b) residue methods. The first

*Prepared by the Subcommittee on Gases in Metals. The membership of the subcommittee was as follows:—J. G. Thompson, Chairman; J. Chipman, C. M. Johnson, B. M. Larsen, D. W. Murphy, M. A. Scheil, F. W. Scott, and F. M. Walters, Jr.

group includes the vacuum fusion and hydrogen reduction methods which depend upon the action of carbon or hydrogen at elevated temperatures to reduce the oxide constituents of the steel, with subsequent determination of the gaseous products of the reduction reactions. The second group includes the iodine, electrolytic, chlorine, mercuric chloride, and acid residue methods which depend upon the removal of the metallic constituents, because of their greater chemical activity or solubility, leaving a residue from which various compounds can be isolated and determined.

Vacuum Fusion Method—The vacuum fusion or hot extraction method for determining total oxygen in irons and steels consists of melting a sample in a previously degassed carbon crucible in a highly evacuated furnace in which the pressure is maintained at about 0.001 mm. of mercury or less. The method is based on the fact that at sufficiently high temperatures all the oxygen containing compounds in the sample are reduced by carbon and converted into gaseous oxides of carbon. The gases evolved during the reaction are pumped off and analyzed, and the quantities of carbon oxides are used to calculate the amount of oxygen in the sample. Since the temperature used in the determination of oxygen is sufficiently high to decompose any nitrides that may be present, nitrogen may be determined on the same sample if a suitable method is used for the analysis of the gases.

The method has developed fairly rapidly since its inception. The early investigations in this field were attempts to melt the sample in refractory crucibles, but Oberhoffer and Hessenbruch¹ showed that it was necessary to carry out the reduction in graphite because of the error introduced by the reduction of the refractory crucible itself. Jordan and Eckman² were the first to apply the high frequency induction method of heating, and also used a gravimetric method of analysis. Hessenbruch and Oberhoffer³ introduced a method of inserting the sample without the necessity of breaking the vacuum.

Since the amount of oxygen in some steels is quite small, it is important that the "blank" correction for gases evolved from the crucible and furnace itself be low. Most of the "blank" gas originates in the crucible itself or at contacts between the hot crucible and any oxide refractories which may be present in the furnace for purposes of thermal insulation. The blank may be reduced to small proportions by proper furnace design and by preparation of the crucible by prolonged heating in vacuum at a temperature 300 to 500°C. hotter than that at which the analysis is conducted.

There are three methods of heating the crucible in use today. The first, and oldest, is the graphite spiral resistor furnace; the second is the high frequency induction furnace which was introduced by Jordan and Eckman² in 1925; the third is the graphite tube furnace recently described by Thanheiser.⁴ Descriptions of modern installations using each of the three methods will be found in the literature cited, references 8-17 inclusive.

The general method of conducting the analysis is as follows: Weighed samples, which must be solid pieces rather than drillings, are placed in the holder at the top of the furnace. The crucible is set up, the furnace closed, and pumps put into operation. The crucible is now brought to a temperature as high as the construction of the apparatus permits, representative figures from several laboratories ranging from 1750-2100°C. After heating for a half hour to two hours the temperature is dropped to that required for the analysis, 1550-1700°C. The pressure and rate of evolution of gas from the crucible are determined and used in computing the "blank".

The sample is dropped into the crucible and heating and pumping are continued until the pressure has returned to its former value; the time required here is from five minutes to two hours, depending upon details of construction and the type of steel analyzed.

The gases evolved may be pumped up to atmospheric pressure and transferred to an apparatus of the Orsat type for analysis or they may be analyzed by one of the simplified low pressure absorption methods described in several of the appended references.

The three chief sources of error in the vacuum fusion method are spattering of metal from the crucible, absorption of the gases by films of volatile metals which may form in the cooler parts of the furnaces, and incomplete reduction of refractory oxides. Trouble encountered in spattering may be overcome by melting samples with high oxygen content slowly under reduced temperature.

Hessenbruch and Oberhoffer³ noted deposits of manganese and aluminum on the walls of the furnace, and attributed low recoveries of oxygen from samples containing high percentages of these elements to the absorption of CO by the finely divided

metallic deposit. Vacher and Jordan⁹ reported the maximum allowable amounts of manganese and aluminum in the samples to be 0.24 and 0.05%, respectively, but Ericson and Benedicks¹⁰ who were the first to use wide, short connections between furnace and pump, placed the limits for manganese and aluminum at 3 and 2%, respectively. No limits for these elements can be accurately placed since the degree of their influence seems to be a function of the particular furnace in question. The influence of these elements is responsible for the move toward higher speed pumps and short, wide connections, since swift removal of the gases seems to cut down this effect by removing the gases before an appreciable film is formed. Other active volatile metals, such as calcium and barium, though rarely present, act in the same way. Thus, the calcium contained in ferrosilicon prevents the determination of oxygen in that alloy.

It has been shown repeatedly that at temperatures over 1550°C. all of the common oxides are completely reduced provided they are in a fine state of subdivision, such as the normal oxide inclusions in steel. When larger lumps of oxide are present, reduction is slow and in certain cases this constitutes a serious source of error.

The method has been applied to many types of plain carbon and alloy steels. It has found its greatest usefulness in the study of steel making methods rather than as a means of inspection of the finished product.

Fractional Vacuum-Fusion Method—Of the various methods now employed for the determination of oxides and gases in ferrous materials the fractional vacuum fusion method yields the most information, for the time involved. The technique and apparatus employed in this method of hot extraction, and the results obtained have been described by Reeve,¹¹ and amplified by Hoyt and Schell.¹² The method is applicable to the study of such materials as rimming, semirimming, and killed carbon steels, certain alloy steels, and cast iron.

The apparatus employed for the fractional method is essentially that used for the "total" oxygen method. The gases from each temperature fraction are collected at atmospheric pressure and analyzed separately by the usual methods of gas analysis. An improvement recently reported by Motok¹³ is extension of the height of the furnace to prevent condensation of metallic tin vapors on the window. This allows more than one analysis to be made without breaking the vacuum in the furnace.

The procedure is essentially as follows: The graphite crucible is outgassed at a high temperature to give a low blank correction which is as essential to the accuracy of this method as it is to that of the "total" oxygen method. After outgassing, the temperature is lowered to about 1550°C. and the amount of tin necessary to completely fuse the ferrous sample is dropped. The tin is allowed to degas before the temperature is lowered to 1000°C. and the base pressure determined. The weighed sample of ferrous material is then dropped into the bath of tin-carbon and the oxides FeO, MnO, SiO₂, and Al₂O₃ (and the gases nitrogen and hydrogen), are separated by a series of temperature fractions at 1050, 1170, 1320, and 1570°C.

The hypothesis concerning fractionation is that since simple oxides such as FeO, MnO, and SiO₂ will react with carbon at progressively increasing temperatures to give up their oxygen, then these oxides will react similarly when present as complex oxides or silicates in ferrous materials. It is likewise assumed that during the time of fractionation, the various oxides retain their own individuality, and that there is no displacement of equilibria to produce interaction between the oxides themselves or with metals such as Fe, Si, and Al which may be present in the sample.

One of the most important sources of error in vacuum fusion methods is the interference from metallic vapors of manganese or aluminum, which are distilled from the molten sample, and which react with carbon monoxide and lead to low recoveries of oxygen. The removal of the evolved gases at high speeds, the avoidance of drastic cooling of the furnace tube,¹⁴ and the use of a fresh graphite crucible⁹ for each determination on high manganese or aluminum killed steels have helped to give normal oxygen determinations for such samples. Furthermore, it has been found¹⁵ that the presence of tin assists in the recovery of oxygen from a high manganese steel. About half of the tin used in this method volatilizes during fractionation and presumably alloys with the metal vapors and lowers their reactivity with CO.

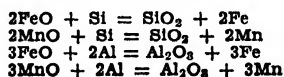
The chief advantage of the fractional vacuum fusion method as compared to the "total" oxygen determination is that knowledge of the distribution of the oxygen content of ferrous materials is obtained. This method allows the separate determination of specific oxides such as FeO, MnO, SiO₂, and Al₂O₃. Other oxides such

as those of chromium, vanadium, and titanium have been found to react at specific temperatures and in some instances have been separately determined. The total of the separately determined oxides is within the limits for total oxygen as determined by the vacuum fusion method.¹

The principal disadvantage of the fractional method, aside from the original cost of the equipment, is the length of time consumed in a determination. The separation of FeO and MnO requires close temperature control and frequent careful pressure readings. Samples high in FeO, especially when the FeO inclusions are massive, require longer dissociation periods, but, on the average, each fraction requires about 30 min. Observation of the time required to complete dissociation of the oxides at the different fraction temperatures may be advantageous at times because it gives the operator an indication of the particle size. The time required to analyze the gases from each fraction in a Type A—Orsat apparatus is between 20 and 30 min.

The following recommendations are offered, for efficient operation of the fractional method: (a) The sample size should be as large as possible to secure greater accuracy, the sample weight depending on the deoxidation treatment of the steel. For well deoxidized steel at least 50 g. of sample is desirable. (b) Substantially all blank gases, for all four fractions, should be eliminated by previous high temperature degassing and the use of a beryllia refractory shield around the graphite crucible. (c) C. P. stick tin with negligible gas content should be used. The amount of tin should be sufficient to completely fuse the ferrous material at 1000-1050°C.

Uncertainties of the fractional method for oxygen are as follows: (a) Reproducibility of results by different operators. Insufficient data are at hand to justify a statement. Check results on the same type of equipment by the same operator have been reported (Reeve, Scheil, Motok). (b) Completeness with which the oxygen from each fraction is extracted. Undoubtedly there is some slight overlapping. However, the results obtained by this method, both for FeO and MnO, are more in keeping with the melting practice and the inclusion content than are those of any other method.¹ There is some uncertainty regarding the complete reduction of alumina. (c) Error introduced by the upsetting of the equilibria. The equations



represent possible reactions but sufficient data are not available to determine the importance of these possible equilibria displacements. However, the remarks under item (b) of this paragraph also apply here.

Hydrogen Reduction Method—This method involves the passage of pure hydrogen over the sample heated to 1100-1200°C. for some selected period (usually between 1 and 2½ hr.), the H₂O, CO, and CO₂ being collected from the exit gases and their corresponding oxygen contents measured. General details of apparatus and method as used by various laboratories may be found in references 21-24 inclusive. Current procedures differ mainly in (a) form of sample and container, (b) method of heating, (c) elimination of surface oxygen, and (d) method of measuring CO and CO₂ in the exit gases.

The sample may be in lump form (10-20 g.) and melted, together with antimony^{21, 22} or antimony and tin, in a refractory boat in a horizontal tube furnace. There is evidence²⁴ that under these conditions, the true blank error is difficult to estimate because part of it (resulting from reduction of oxides in the containing boat or furnace tube) occurs only when the metal sample is present. The alternative method²⁴ is to use inductive heating and a sample* of thin millings in a degassed metal bucket suspended in a quartz bulb. Very low and accurately known blanks may be obtained, but the method brings its added complication in the surface oxygen on the thin millings. This surface oxygen, plus adsorbed oxygen or H₂O on the container and bulb surface is removed by heating all these parts in a resistance furnace at about 600°C., which lengthens the time for analysis and may cause the loss of a small portion of the contained oxygen in certain high oxygen samples. However, this latter method probably is more accurate and reproducible.

*In sampling rolled steel products of various forms, care should be taken that the pieces or chips used represent the average cross section perpendicular to the rolling direction, since such samples are often quite variable over this cross sectional area. This precaution should be common to all methods.

In the exit gases the percentage of the total oxygen present as H_2O varies from about 80-90% for low carbon samples, such as electrolytic iron or "low metalloid" steel, down to only 5-10% for medium and high carbon steels, the remainder being CO and CO_2 , which thus comprise the bulk of the oxygen from most steel samples. The H_2O portion is always collected in a P_2O_5 weighing tube, but the CO and CO_2 portions are collected either by (a) oxidizing the CO to CO_2 with a hot solution of iodine pentoxide and collecting CO_2 ,^{23, 24} or (b) by reducing both the CO and CO_2 to CH_4 and H_2O over a reduced nickel catalyst^{21, 24} and collecting the H_2O in a second P_2O_5 tube. A number of other methods of course are possible²¹ but the foregoing are favored in present practice. As to the accuracy of the iodine pentoxide method, the available data are really not adequate; the oxidation of CH_4 , which is nearly always present is one possible source of error in this method. The catalytic reduction method appears to give accurate results under optimum conditions. The nickel catalyst, in order to be active enough to give quantitative conversion to H_2O , must be reduced at such a low temperature that some residual nickel oxide is apparently always present. In addition to periodic checks on its activity, it must also be heated occasionally to 60 or 80° above its operating temperature (250-270°C.) for 6-10 hr. with hydrogen flowing, to maintain the desired accuracy.

Certain evidence²⁴ indicates that in ordinary steels, in addition to a fairly rapid recovery of dissolved oxygen and FeO, there is a much slower reduction of SiO_2 , MnO, and Cr_2O_3 , and possibly also of Al_2O_3 , TiO_2 , and other oxides when present in very fine particles. With 1.5-2.5 hr. of heating at 1100-1200°C., between 70 and 95% of the values obtained therefore represent dissolved and FeO oxygen, an absolute separation of the various forms of oxygen being impossible. Also, to obtain the most accurately comparable values, the conditions of time and temperature of reduction should be held constant for any group of samples.

Recent studies¹ show that we are still unable to give a reliable opinion as to the absolute accuracy of this, or indeed of any of the other methods for oxygen analysis in ordinary steels. Under optimum conditions it has been found²⁴ to give reproducible results to within 0.002% O₂ and has been useful in comparing samples made under similar conditions of manufacture. With some exceptions, the values obtained have not been found to be informative when different types of steel are compared as to oxygen contents. It would be especially doubtful to compare values on high silicon or chromium steels with carbon or low alloy steels. In general, however, the method can be used for nearly all types of low and high alloy steel, pure iron, and cast iron as well as nickel. The method can also be used for copper with a lower reduction temperature of around 950-1000°C.

The method requires between 2½ and 5 hr. for a single analysis. Skillful technique and a vacuum tight train are essential.

Iodine Method—When a sample of steel is treated with a suitable solution of iodine, the iron, silicon and manganese are dissolved and a residue of carbonaceous material (carbides in certain cases) and unattacked oxides remains.

In the procedure described by Cunningham and Price,²⁵ a sample weighing from 5-10 g. is treated at 3°-5°C. in a stoppered flask with an aqueous solution of iodine in ferrous iodide. After the sample has completely dissolved the solution is filtered and the insoluble residue is thoroughly washed to remove ferrous iodide, iodine, and other contaminants. The residue is then ignited, weighed and fused with sodium carbonate. The fusion is dissolved in hydrochloric acid and the SiO_2 , Al_2O_3 , MnO, and FeO contents of the solution are determined by the usual procedures of chemical analysis. It is claimed that sulphides and nitrides are decomposed by the ferrous iodide treatment and that the procedure is applicable to the analysis of plain carbon and manganese steels. Carbides of certain elements, for example chromium and vanadium, are not decomposed by the ferrous iodide treatment and, if present, lead to erroneous results in the determination of the oxide content of the residue.

In the procedure described by Rooney, Stevenson, and Raine,²⁶ the sample is treated with a solution of iodine in anhydrous methyl alcohol. Rather elaborate precautions are necessary to exclude moisture and oxygen from the solvent and containers while the steel is dissolving and during filtration of the resulting solution. After filtration and washing the residue is subjected to the usual procedure of chemical analysis for the determination of SiO_2 , FeO, Al_2O_3 , and MnO. Small amounts of Cr_2O_3 , ZrO_2 , and TiO_2 are sometimes found in the residues from plain carbon steels but these were probably present in the steel as carbides. The procedure suffers from interference by the presence of alloying elements of the carbide forming type and further work remains to be done to determine the role of sulphides and phosphides.

Willems²⁷ recommended the use of a solution of iodine in absolute ethyl alcohol and subsequent filtration through an ultra filter.

The principal advantages of the iodine method are the relatively low operation cost and the identification of individual oxides in the residue. On the other hand, the method is relatively slow, the analyst must be highly skilled in the difficult and complicated procedure, and the effect of carbides, sulphides and phosphides should be further studied. The results of the co-operative analysis showed that the aqueous iodine method in the hands of a skilled operator is accurate for the analysis of aluminum killed steels and of some silicon killed steels but that low recoveries of oxygen and oxides are obtained from other silicon killed steels and from rimming steels. Satisfactory concordance in the results obtained by different operators using the iodine method, particularly for the determination of FeO, is not yet attainable.

Electrolytic Method—The principle of the electrolytic method of oxide extraction is the same as the chemical solution method in that the metallic constituents are separated from the nonmetallics, and the oxides are determined in the residue. The sample is the anode of the cell, and the electrolyte should decompose all non-metallics except the oxides.

The study of methods for electrolytic extraction of oxides started with the publication, in 1929, of a paper by C. H. Herty, Jr.²⁸ concerning the theoretical aspects of obtaining the oxide residue from steel by electrolysis. Most of the research has been to find a suitable electrolyte, which must be neutral, have no solubility for MnO and manganese silicates or aluminates, and have an anion whose decomposition potential is lower than that of oxygen. This latter qualification is important as any formation of oxygen at the anode will cause serious contamination of the oxide residue. Also the anion must completely decompose other nonmetallics. Of all the anions considered, iodine has the greatest possibility of successful application.

Fitterer²⁹ in 1931 described an electrolytic method for the analysis of both oxides and sulphides using a solution of ferrous sulphate and sodium chloride for the electrolyte. Iron oxide could not be determined because of the voluminous precipitate of iron hydroxide during the electrolysis. Recent work by this method, on silicon treated carbon steels shows that the oxide residue contains silicic acid and carbides. Also the heat treatment of the sample affects the results.

In 1932, Treje and Benedicks³⁰ proposed the use of an electrolyte of sodium citrate and potassium bromide for oxide and sulphide extraction. This method was to be used on low carbon steel or iron as carbides were not decomposed. Apparently the sulphides were not quantitatively recovered and the residue contained silicic acid, metallics and carbides. Since the electrolyte increased in acidity during the electrolysis, only a small sample could be extracted before serious attack upon the oxide residue began.

In 1933, Styri³¹ described the use of an acid electrolyte for the extraction of oxides and sulphides. He found that the residue contained sulphides and carbides and some metallics. With the proper control of acidity, and heat treatment of the specimen to bring the carbon into solution, the method offered some promise for sulphides, silica, and alumina.

In 1932, Scott³² described an electrolytic method, with a magnesium iodide electrolyte, which combined the desirable features of the iodine solution method with those of electrolytic extraction. Using slags taken from "rimming" steel ingots, that were rich in manganous oxides and manganese-rich silicates, he determined that the recovery of the manganese compounds was high; over 80% for pure manganous oxides and 100% for silicon treated steels. Subsequent work demonstrated that all sulphides, phosphides, and carbides were completely decomposed, and with proper treatment of the residue, no contamination resulted from silicic acid.

Magnesium iodide as an electrolyte has many desirable properties. It is highly ionized, with resulting high conductivity. A fresh solution has a pH value of 8.5 which drops to approximately 5.3 after 200 hr. electrolysis. No oxygen is evolved at the anode as iodine has a decomposition potential considerably lower than oxygen. Hydrogen is evolved at the cathode, and magnesium is precipitated as the hydroxide, necessitating the addition of more magnesium iodide at intervals of 100-200 hr. The plating properties of the solution are good, and metallic iron and manganese are plated out, keeping their concentration low in the electrolyte.

High carbon steels and irons may be extracted with as great accuracy as low or medium carbon steels. If the specimen is difficult to decompose iodine plates out on the sample, combining the electrolytic effect with the solution principle by increasing the iodine concentration near the sample. The resulting rate of reaction

is slower, but the completeness of the reaction is unimpaired. In a recent paper³³ Hare and Soler reported that the method is applicable not only to all carbon steels but to nickel steels, low molybdenum, and certain low chromium steels. Joseph³⁴ described the application of the method to the determination of oxides in basic pig iron. Nearly 900 samples were extracted and analyzed over a period of about 9 months, with two men operating 12 cells.

The treatment and washing of the residue is of utmost importance after the extraction, and before the analysis. A complete description of the washing and an outline of the analytical procedure has been published in the paper by Joseph.³⁴ As carbon has the property of absorbing large quantities of salts, complete washing can only be accomplished by digesting the residue in the described manner, and thorough washing. These comments on the importance of complete washing and proper selection of analytical procedure apply to all residue methods.

Chlorine Method—If a sample of steel is heated at moderately elevated temperature in a stream of purified chlorine, the metallic constituents are converted to chlorides which are largely volatile under these conditions. The oxide constituents are not attacked by the chlorine and may be determined by suitable means in the residue from the chlorination treatment.

Procedures for the chlorine method have been described recently by Dickens,³⁵ Meissner,³⁶ Wasmuht,³⁷ Klinger and Fucke,³⁸ and Colbeck, Craven, and Murray.³⁹ Chlorination temperatures as low as 300°C. have been recommended on the grounds that some of the oxides are attacked by chlorine at higher temperatures, and have been criticized because of the difficulty of complete elimination of metallic constituents. Wasmuht reported that chlorination at temperatures of at least 500°C. was necessary for chromium, tungsten, and other alloy steels. Sufficient data are not yet available to define either the accuracy or the reproducibility of results by the chlorine method. It has been suggested that sulphides and phosphides probably do not interfere with the operation of the chlorine method, as they do in the iodine method.

Mercuric Chloride Method—In the mercuric chloride method, the sample is subjected to the action of an aqueous solution of mercuric chloride, 120 g. per liter. In the absence of air the reaction proceeds as follows:



Metallic iron thus goes into solution as ferrous chloride whereas FeO and MnO remain in the insoluble residue, from which they may be isolated or determined by suitable means. The determination of SiO₂ and Al₂O₃ is not attempted. The method was proposed by Maurer in 1909 and has been recently described in detail by Maurer, Klinger and Fucke.⁴⁰

Compounds of manganese and iron with phosphorus, sulphur, and nitrogen are not decomposed quantitatively. The presence in the insoluble residue of these compounds, or of metallic particles from incomplete decomposition of the sample, leads to high results for FeO and MnO. The limited number of determinations by the mercuric chloride method, that were reported in the cooperative analysis, showed that satisfactory results usually were obtained for MnO but that the results for FeO were consistently high. These data indicate that incomplete solution of the sample, resulting in the presence of metallic particles in the residue, is perhaps a more serious source of error than the presence of phosphide and sulphide compounds.

Nitric Acid Method—This method was developed by Dickenson⁴¹ and was thoroughly investigated by Herty and his associates.⁴² The method depends upon the solubility of metallic constituents and the relative insolubility of oxides, particularly alumina, in approximately 10% nitric acid.

Accurate results for Al₂O₃ are obtained by this method but the determination of SiO₂ is less satisfactory. There are two principal sources of error in the latter determination: (a) High results may be obtained because of the presence in the residue of hydrated silicic acid, formed during the solution of metallic silicides, and (b) Low results for SiO₂ may be caused by partial solubility of some of the silicates that occur in steel, particularly the less siliceous silicates.

FeO and MnO are quite soluble in dilute nitric acid and, therefore, are not determinable by this method.

Hydrochloric Acid Method—The use of dilute hydrochloric acid to effect the separation of metallic and nonmetallic constituents of steel was recommended by Kichline⁴³ for the determination of alumina. Additional data on the determination of silica as well as alumina were reported by Thompson and Acken.⁴⁴

The hydrochloric acid method yields accurate results for Al_2O_3 , but determinations of SiO_2 are less satisfactory. In the latter determination the chief sources of error are the presence of hydrated silicic acid in the residue and the partial solubility of certain silicates. The method is not applicable for the determination of FeO and MnO . The hydrochloric acid method resembles the nitric acid method in basic principles and in results obtained, but is preferable on the grounds of speed and simplicity of operation.

Methods for the Determination of Nitrogen—Nitrogen exists in ferrous materials chiefly in the form of metallic nitrides; the amounts of nitrogen that exist in solid solution or in the free state usually are of minor importance. In simple steels the nitrogen is present chiefly as iron nitride, but in modern steels, particularly alloy steels, other nitrides may be present in appreciable amounts.

Two procedures are in common use for the determination of nitrogen, the vacuum fusion and solution distillation procedures, and the results obtained by the two methods are usually in excellent agreement. Other methods that have been proposed for the determination of nitrogen include combustion in oxygen and fusion with sodium peroxide in a vacuum. In both methods nitrogen is recovered from the gaseous products of the reaction. The combustion method was described by Sawyer;⁴⁶ the method of fusion with sodium peroxide was proposed by Klinger.⁴⁷

In the vacuum fusion procedure, the conditions that produce reduction of the oxides likewise bring about decomposition of the nitrides, with liberation of elemental nitrogen which is collected and subsequently determined as the residual gas after absorption of carbon oxides and water vapor. All of the nitrides present in simple steels are readily decomposed, but Thompson and Hamilton⁴⁸ observed that the nitrides present in a nitriding steel (1.3 Cr, 0.16 Mo, 1.06 Al) were decomposed slowly.

As a result of his extended study of the fractional vacuum fusion method, Scheil believes that nitrides as well as oxides are fractionated by this procedure. This suggests that the various nitrogen fractions represent different combinations of nitrogen with other elements in the steel, although the nitrogen compounds may be present to some extent in solution or combination with the respective oxides and are released only when the oxides are reduced.

The solution distillation method for the determination of nitrogen depends upon the fact that when a steel sample, in the form of drillings or millings, is dissolved in hydrochloric acid the nitrogen of the metallic nitrides is converted to ammonium salts. If the solution is then made alkaline and boiled, these salts are decomposed with the liberation of ammonia. Determination of the amount of ammonia distilled from the solution furnishes a measure of the nitride nitrogen present in the steel sample. The procedure was originated by Allen,⁴⁹ in 1880. Jordan and Swindells⁵⁰ traced the development of the method and introduced improvements in the determination of the distilled ammonia and in the use of block tin in place of glass condensers to make the blank correction smaller and more uniform. Scott⁵¹ advocated the use of the iodide-iodate reaction, to avoid difficulty in the titration of the distilled ammonia.

In the early work with the solution distillation method it was assumed that all metallic nitrides were decomposed either by the hydrochloric acid or by the subsequent action of the sodium hydroxide solution. This assumption was permissible for simple steels, but it was now evident that modern alloy steels contain nitrides that are not decomposed by the simple Allen procedure. Johnson⁵² reported that the nitrides of V, Ti, Nb, and Zr were not completely decomposed in the ordinary procedure of solution in hydrochloric acid but were decomposed by a boiling mixture of perchloric and concentrated sulphuric acids. Subsequent work has shown that a combination of perchloric and hydrochloric acids is equally efficient.

The procedure now in use in Johnson's laboratory, for the determination of nitrogen in chromium metal, ferrochromium, chromium-nickel-molybdenum carbide steels, and plain carbon steels is, briefly, as follows:

The size of the sample, drillings or fine powder, varies from 1-5 g. or more depending on the nitrogen content. Place the weighed sample in a 600 ml. beaker, add 60 ml. of 1:1 HCl , cover, and digest on a hot plate, but do not boil. After solution of the sample is complete and evolution of hydrogen has ceased, boil the solution to reduce its volume to about 35 ml. Remove from the hot plate, add 60 ml. of 60% C. P. perchloric acid. Heat to heavy fumes of HClO_4 and continue fuming until the volume is reduced to about 20 ml. Allow beaker and contents to cool, add 200 ml. H_2O , boil 20 min. to dissolve all salts and allow to cool.

Subsequent steps in the determination are as described in detail in the article

previously cited.²³ The solution is transferred to a Kjeldahl flask, made alkaline, and boiled. The evolved ammonia is collected in a known volume of standard acid. Titration with standard NaOH, using alizarine for an indicator, furnishes a measure of the amount of NH_4OH in the distillate and hence of the amount of nitrogen in the steel sample.

The accuracy of the HCl-HClO_4 procedure has been demonstrated by comparison with results obtained by the vacuum fusion method and by an acid solution method in which sulphuric acid was used instead of the HCl-HClO_4 solvent. For many steels the results of all three procedures are in excellent agreement; for some materials, for example high carbon ferrochromium, the solution distillation methods yielded somewhat higher values for nitrogen than were indicated by a vacuum fusion determination. The HCl-HClO_4 treatment is definitely preferable to the H_2SO_4 procedure for the analysis of steels that contain insoluble carbides.

Methods for the Determination of Hydrogen—The vacuum fusion procedure is generally employed for the determination of the small amounts (usually less than 0.001%) of hydrogen that exists in ferrous materials.

In the vacuum fusion procedure, which was described in detail in the section devoted to the determination of oxygen, the hydrogen present in the sample is liberated together with nitrogen, from decomposition of the nitrides, and carbon monoxide from reduction of the oxides. The carbon monoxide and hydrogen are oxidized to CO_2 and H_2O respectively and the oxidized gases are absorbed separately. The gain in weight of the absorbent for H_2O , or the decrease in volume or pressure of the gas mixture as a result of the absorption of H_2O vapor, furnishes a measure of the amount of H_2O and hence of the amount of hydrogen evolved from the sample.

Schell has observed that hydrogen as well as nitrogen and oxygen is fractionated in the fractional vacuum fusion procedure and the total of the hydrogen fractions is usually higher than that obtained in the nonfractional procedure. As yet no satisfactory explanation of these observations has been offered but it has been suggested that the presence of tin may favor the evolution of hydrogen, perhaps by decreasing its solubility in the steel. Körber and Ploum²⁴ considered that the hydrogen evolved in a vacuum extraction at 400°C . was diffusible hydrogen whereas the hydrogen evolved at higher temperatures was present in the steel in a combined form. In general, steels charged with hydrogen evolved appreciable quantities of gas at 400°C . and smaller amounts at higher temperatures whereas normal steels, not specially charged with hydrogen, evolved little or no gas at 400°C . but did evolve hydrogen when heated to approximately 1000°C . This evidence indicates the existence of metal hydrides in steel.

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Etching Reagents for Microscopic Examination of Steels and Irons*

(Only reagents of high analytical purity should be used.)

I. General Reagents for Irons and Steels (Carbon, Low and Medium Alloy Steels)

No.	Etching Reagent	Composition	Uses	Remarks
1.	Nitric acid (Nital)	Nitric acid, sp.gr. 1.42 1.5 ml. Ethyl or methyl alcohol, 95% or absolute 100 ml. (also amyl alcohol)	In carbon steels (1) to darken pearlite and give contrast between pearlite colonies; (2) to reveal ferrite boundaries; (3) to differentiate ferrite from martensite.	Etching rate is increased, selectively decreased, with increasing percentages of HNO ₃ . Reagent 2 (picric acid) usually superior. 4% in amyl alcohol useful for grain boundary and contrast of low carbon materials. Etching time, a few seconds to a minute.
2.	Picric acid (Picral)	Picric acid..... 4 g. Ethyl or methyl alcohol, 95% or absolute 100 ml. (Use absolute alcohol only when acid contains 10% moisture or more.)	For all grades of carbon steels (1) annealed, (2) normalized, (3) quenched, (4) quenched and tempered, (5) spheroidized, (6) austempered. For all low alloy steels attacked by this reagent.	Superior to reagent No. 1 except for those specific uses listed thereunder. More dilute solutions occasionally useful. Does not reveal ferrite grain boundaries as readily as No. 1. Etching time a few seconds to a minute or more. See Reference 2.
3.	Hydrochloric and picric acids	Hydrochloric acid. 5 ml. Picric acid..... 1 g. Ethyl or methyl alcohol, 95% or absolute 100 ml.	For revealing the austenite grain size in quenched, and quenched and tempered, steels.	Best results are obtained when the martensite is tempered for 15 min. at 400-475°F.
4.	Chromic acid	Chromic acid..... 10 g. Water 100 ml.	For various structures except grain boundaries of ferrite. Attacks cementite very rapidly, austenite less rapidly, ferrite and iron phosphide very slowly if at all.	Used electrolytically, the specimen as anode, the cathode stainless steel or platinum, $\frac{3}{4}$ -1 in. apart; 6 volts usually used. Time of etching 30-90 sec. depending on specimen. M. Baeyertz, Trans., A.S.M., 1937, v. 25, p. 1185.
5.	Heat tinting	Heat only.	Pearlite first to pass through a given color, followed by ferrite; cementite less affected, iron phosphide still less. Especially useful for cast irons.	Clean, dry polished specimen heated face upon hot plate to 400-700°F. Time and temperature both have decided effects. Bath of sand or molten metal may be used. See Reference 1.

II. General Reagents for Alloy Steels (Stainless and High Speed Steels)

No.	Etching Reagent	Composition	Uses	Remarks
6.	Ferric chloride and hydrochloric acid	Ferric chloride... 5 g. Hydrochloric acid. 50 ml. Water 100 ml.	Structure of austenitic nickel steels.	
7.	Aqua Regia	Hydrochloric acid. 75 ml. Nitric acid 25 ml.	Structure of stainless steel.	Mixture should stand 24 hr. before using; used full strength for rapid work, but requires careful handling.
8.	Chrome Regia	Hydrochloric acid. 25 ml. Chromic acid, 10% water solution... 5-50 ml.	Heat treated 18-8 stainless steels.	Activity is controlled by amount of chromic acid.
9.	Ferric chloride and nitric acid	Saturated solution of ferric chloride in hydrochloric acid, to which a little nitric acid is added.	Structure of stainless steel.	Use full strength.

(Continued)

*Prepared by the Subcommittee on Etching Solutions for Iron and Steel. The membership of the subcommittee was as follows: G. T. Williams, Chairman; Miss M. Baeyertz, G. F. Comstock, O. E. Harder, L. F. Lottier, Miss M. Norton, H. S. Rawdon, J. R. Villella.

The assistance of Mr. A. L. Sanford is also acknowledged.

No.	Etching Reagent	Composition	Uses	Remarks
10.	Mixed acids in glycerol	A. Nitric acid.....10 ml. Hydrochloric acid .....20-30 ml. Glycerol .....20-30 ml. B. Nitric acid.... 10 ml. Hydrofluoric acid. 20 ml. Glycerol .....20-40 ml. C. Nitric acid.... 10 ml. Hydrochloric acid. 20 ml. Glycerol 20 ml. Hydrogen peroxide 10 ml.	Structure of iron-chromium base alloys, high speed steels, and austenitic manganese steel. Etches nickel-chromium alloys satisfactorily. Structure of high silicon alloys of the Duriron type. For etching iron-chromium nickel, iron-chromium manganese, and all other austenitic iron-chromium base alloys.	Warm specimen in water before etching. For best results use method of alternate polishing and etching. If given sufficient time, will etch totally austenitic alloys, but better results are obtained by using reagent 10-C. Amount of glycerol may be varied to suit metal. Amount of hydrochloric acid may be varied if reagent acts too rapidly or slowly. For best results employ method of alternate polishing and etching.
11.	Oxalic acid	Oxalic acid..... 10 g. Water .....100 ml.	For austenitic stainless steels and high nickel alloys. Carbides and general structure revealed depending on etching time.	Used electrolytically, the specimen as anode, the cathode stainless steel or platinum, about 1 in. apart; 6 volts usually used. Precipitated carbides in stainless steels may be revealed in 10-15 sec., the general structure in about 1 min. For study of carbides, 1.5-3 volts may be used, thus increasing the etching time and improving control of etch.
12.	Mixed acids and cupric chloride	Hydrochloric acid. 30 ml. Nitric acid..... 10 ml. Saturate with cupric chloride and let stand 20-30 min. before use.	For stainless alloys and others high in nickel or cobalt.	Apply by swabbing.
13.	Nitric and acetic acids	Nitric acid..... 30 ml. Acetic acid..... 20 ml.	For stainless alloys and others high in nickel or cobalt.	Apply by swabbing.
14.	Hydrochloric and nitric acids in alcohol	Hydrochloric acid. 10 ml. Nitric acid..... 3 ml. Methyl alcohol....100 ml.	To reveal the grain size of quenched, or quenched and tempered high speed steel.	Etch 2-10 min. Snyder and Graff, Metal Progress, 1938, v. 33, p. 377.
15.	Ferricyanide solution	Potassium ferricyanide 30 g. Potassium hydroxide 30 g. Water 60 ml.	To distinguish between ferrite and sigma phase in iron-chromium, iron-chromium-nickel, iron-chromium-manganese and related alloys. Colors sigma phase light blue, ferrite yellow.	Must be fresh. Use boiling. Burgess and Forger, A.I.M.E. Tech. Pub., April 1938.
16.	Cupric sulphate	Cupric sulphate... 4 g. Hydrochloric acid. 20 ml. Water 20 ml.	Structure of stainless steels.	Marble's reagent.
3.	Hydrochloric and picric acids	Hydrochloric acid. 5 ml. Picric acid..... 1 g. Ethyl or methyl alcohol, 95% or absolute .....100 ml.	For etching many steels of the iron-chromium, iron-chromium-nickel, and iron-chromium-manganese types.	Reference 2.

III. Phosphorus Segregation, Phosphides, and Strain Lines

No.	Etching Reagent	Composition	Uses	Remarks
17.	Cupric chloride	A. Cupric chloride 1 g. Magnesium chloride 4 g. Hydrochloric acid 1 ml. Water 20 ml. Alcohol, absolute...100 ml. B. Cupric chloride 5 g. Hydrochloric acid. 40 ml. Water 30 ml. Ethyl alcohol..... 25 ml.	For showing segregation of phosphorus or other elements in solid solution; copper tends to deposit first on areas lowest in phosphorus. To reveal strain lines and their microstructure, and precipitation hardening in steel.	Dissolve salts in least possible quantity of hot water. Etch for about 1 min. repeating if necessary. Stead's reagent. May be used cold. Etching time, about 10 sec. Fry's reagent.

(Continued)

No.	Etching Reagent	Composition	Uses	Remarks
18.	Sodium picrate, neutral	Sodium picrate... 1 g. Water .....100 ml. (Wash salt well with alcohol to remove excess acid or alkali)	Shows difference between phosphides and cementite; iron phosphide attacked, cementite unattacked.	Use boiling. Etching time 20 min.
19.	Chromic acid and heat tinting	Chromic acid..... 8 g. Water .....100 ml. Followed by heat tinting.	Distinguishes between iron phosphide and cementite in phosphide eutectic of cast iron; iron phosphide is colored darker.	Etch first in picric acid (No. 2) then for 1 min. in chromic acid; heat tint by heating face upon hot plate at about 500°F. for 1 min.

IV. Structure and Depth of Case of Nitrided Steels

No.	Etching Reagent	Composition	Uses	Remarks
20.	Cupric sulphate and cupric chloride	Cupric sulphate...1.25 g. Cupric chloride...2.50 g. Magnesium chloride 10 g. Hydrochloric acid. 2 ml. Water .....100 ml. Dilute above solution to 1000 ml. with 95% ethyl alcohol.	For showing total depth, structure, and various zones of nitrided chromium - vanadium steels and Nitralloy.	Proportions must be accurate. Etch by immersion to avoid confusing edge effects.
21.	Picric and nitric acids	4% picric acid (No. 2) .....10 parts 4% nitric acid (No. 1) 1 part	For depth of case and structure of Nitralloy.	Best results are obtained when the specimen is annealed in lead at 1475°F. before etching.
1.	Nitric acid (Nital)	Nitric acid..... 2 ml. Ethyl or methyl alcohol, 95% or absolute .....100 ml.	For structure and depth of case of nitrided steels.	
16.	Cupric sulphate	Cupric sulphate... 4 g. Hydrochloric acid. 20 ml. Water 20 ml.	Total depth of nitrided case.	Marble's reagent.

V. Carbides, Nitrides, Tungstides, and Their Differentiation

No.	Etching Reagent	Composition	Uses	Remarks
22.	Sodium picrate, alkaline	Picric acid..... 2 g. Sodium hydroxide 25 g. Water .....100 ml.	Colors cementite, but not carbides high in chromium; in tungsten steels, iron tungstide (Fe_3W) and iron tungsten carbide ($\text{Fe}_3\text{W}_2\text{C}$) are colored more rapidly than cementite, but tungsten carbide is unaffected; attacks sulphides. Delineates grain boundaries in hyper-eutectoid steels in slowly cooled condition.	Use boiling, 5-10 min., or preferably, electrolytically at room temperature; for the latter, specimen is anode, cathode is platinum or stainless steel; with 6 volts, about 40 sec. is usually sufficient.
23.	Hydrogen peroxide and sodium hydroxide	Hydrogen peroxide 10 ml. Sodium hydroxide 10% solution in water 20 ml.	Attacks and darkens iron tungstide in carbon-free iron tungsten alloys. When carbon is present this solution darkens the compound ($\text{FeW} + \text{WC}$?) in proportion to the amount of carbide present; tungsten carbide is darkened.	Must be fresh. Etching time 10-12 min.
24.	Ferricyanide solution	A. Potassium ferricyanide 1-4 g. Potassium hydroxide 10 g. Water .....100 ml.	Differentiates between carbides and nitrides; cementite is blackened, pearlite turned brown, and massive nitrides remain unchanged.	Must be freshly made; etch 15 min. in boiling solution.

(Continued)

No.	Etching Reagent	Composition	Uses	Remarks
24. (Continued)		B. Potassium ferricyanide 10 g. Potassium hydroxide 10 g. Water 100 ml.	Darkens carbide containing chromium, carbides and tungstides in tungsten and high speed steels. At room temperature colors ternary carbides ($\text{Fe}_3\text{W}_2\text{C}$ or $\text{Fe}_2\text{W}_6\text{C}$) in a few seconds, iron tungstide (Fe_3W_3) in several minutes, and barely colors cementite.	May be used cold, but preferably hot, should be freshly made, etching time 5-10 min. Murakami's reagent.
25. Sodium cyanide		Sodium cyanide... 10 g. Water 90 ml.	Darkens carbides without attacking austenite or grain boundaries.	Used electrolytically, the specimen as anode, cathode, similar material, about 1 in. apart; 6 volts (not less than 5). Etching time 5 min. or more. W.B. Arnes, Trans. A.S.M., 1936, v. 24, p. 701.
4. Chromic acid		Chromic acid..... 10 g. Water 100 ml.	Attacks carbides in stainless steels very rapidly, austenite less rapidly, and ferrite very slowly if at all. For various structure of stainless steels.	See solution No. 4 in Section I.
11. Oxalic acid		Oxalic acid..... 10 g. Water 100 ml.	To reveal carbides in stainless steels.	See No. 11 in Section II. If strongly etched general structure is revealed; therefore for study of carbides reduced voltage is used for etching, giving better control of etch.

References

The following general references should be consulted when more elaborate discussion is required.

- T. Berglund, *Metallographers' Handbook of Etching*, Isaac Pitman & Sons, New York, 1931.
- J. R. Vilella, *Metallographic Technique for Steel*, A.S.M., 1938.
- A. Portevin and P. Bastien, *Réactifs d'Attaque Métallographique*, Paris, 1937.

Macro Etching of Iron and Steel*

Part I

General—Macro etching of iron and steel consists of subjecting the metal to the action of a reagent in order to bring out the structure for visual inspection. Macro etching implies, to many people, merely routine inspection; however, as shown in the tabulation below, macro etching is widely used for many purposes.

Preparation of Sample—The preparation of the surface of the test specimen is governed by the intensity of the action of the reagent employed. Weak etching solutions require polished surfaces. Those solutions of a strength to produce a deep attack do not require as much care in sample preparation.

Unless otherwise noted, the samples should be in a soft condition. When, however, hardened material is to be etched, great care should be exercised so that the metal is not affected by the heat of grinding or cutting.

The surface required for each reagent is designated under the heading "Remarks" by the letters A, B, or C. Type A represents a saw cut or machined surface; B average ground surface; and C, polished surface. When using Type A surface, consideration must be given to the type of steel. For the higher carbon steels and for tool steels in general a cleanly sawed disc will produce very good results. On the very soft steels, a machined surface not too coarsely cut or a sawed surface, rough ground to remove all traces of flowed metal is desirable.

The compilation of etching solutions for macro etching that follows has been largely taken from Berglund's "Metallographers' Handbook of Etching." In making this compilation, an effort has been made to list the reagents under an alphabetical arrangement of the purposes for which the



Fig. 1—Section of embrittled boiler drum. Etched in hydrochloric acid.

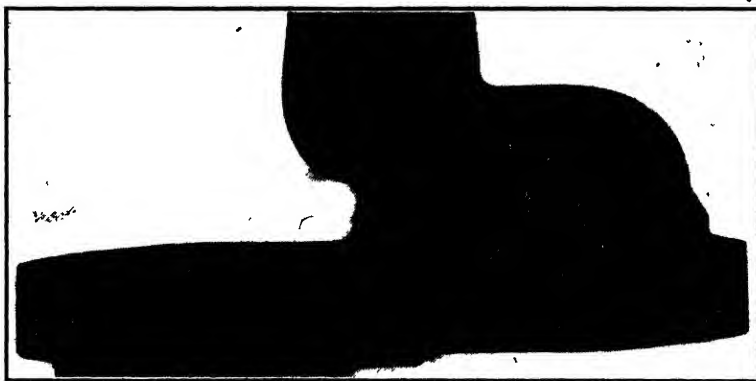


Fig. 2—A longitudinal section showing flow lines.

reagents are intended. Different conditions will be revealed in the same steel by etching with different solutions, and it is well to be familiar with each in order to correctly interpret the results.

*Prepared by the Subcommittee on Macro etching. The membership of the subcommittee was as follows: M. W. Dalrymple, Chairman; R. L. Dowdell, Adam Steever, G. V. Luerssen, J. H. Higgins, and M. G. Yatsevitch.

Solutions for Macro Etching

Purpose	Composition	Remarks	Uses
Blowholes	10% sulphuric acid in water.	Use cold on large sections for 24 hr. Surface B.	Shows blowholes, porosity, pipe, and inclusions.
Blowholes	50% hydrochloric acid in water.	Use at 160-175°F. for ½ hr. Surface A.	Shows blowholes, porosity, pipe, and inclusions.
Carburized case	5% solution of nitric acid in alcohol.	Etch at room temperature. Surface B.	Shows depth of carburized case.
Contrast	1 part iodine; 2 parts potassium iodide; and 10 parts water.	Use at room temperature. Surface B.	Produces contrast for photographing.
Cracks	5% solution of nitric acid in alcohol.	Etch at room temperature. Etches within ½ hr. Surface B.	Detects fatigue, service, hardening and grinding cracks.
Cracks	Hydrochloric acid.	Apply cold with swab.	Detects embrittlement cracks in steam boiler drum. (See Fig. 1.)
Cracks	50% hydrochloric acid in water.	Use at 160-175°F. for ½ hr. Surface B.	Detects fatigue, service, hardening, grinding, and internal cracks. If hardened, material should be softened prior to etching.
Cracks	Kerosene and whiting test.	Wash surface with kerosene. Wipe off. Paint with thin mixture of whiting and water. Let dry. Kerosene in cracks, if present, will discolor whiting. Surface B.	Detects fatigue, service, hardening and grinding cracks.
Cracks	120 g. copper ammonium chloride; 50 cc. concentrated hydrochloric acid, 1000 cc. water.	Etch first with a neutral solution to remove machine marks. Use cold for 20 min. to ½ hr. Surface B.	Produces a strong relief effect. Shows up dendrites and may indicate cracks.
Decarburization	5% nitric acid in alcohol.	Etch at room temperature. Surface C.	The decarburized areas will be light. Area not decarburized dark.
Defects	10% sulphuric acid in water.	Use cold on large sections for 24 hr. Surface B.	Shows porosity, pipe, blowholes, and inclusions.
Defects	50% hydrochloric acid in water.	Use at 160-175°F. for ½ hr. Surface A or B.	Shows porosity, pipe, blowholes, and inclusions.
Defects	2 parts concentrated sulphuric acid; 1 part concentrated hydrochloric acid, 3 parts water.	Use at 160-175°F. for at least ½ hr. Surface A.	Shows general structure and defects.
Dendrites	2 parts concentrated sulphuric acid, 1 part concentrated hydrochloric acid; 3 parts water.	Use at 160-175°F. for at least ½ hr. Surface A.	Shows general dendritic structure and defects.
Dendrites	50% hydrochloric acid in water.	Use at 160-175°F. for at least ½ hr. Surface A.	Shows general dendritic structure and defects.
Dendritic pattern	25% sulphuric acid in water.	Use cold, 8-16 hr. Surface B.	Shows dendritic pattern and flow lines.
Dendritic pattern	40 g. ferric chloride; 3 g. cupric chloride; 40 cc. hydrochloric acid; 500 cc. water.	Etch first with 10% nitric acid. Surface B.	Shows dendritic pattern or structure.
Etch, universal...	500 cc. hydrochloric acid; 70 cc. sulphuric acid; 180 cc. water.	Use at 160-175°F. for 1-2 hr. Surface A.	Good universal etch.
Fiber	10-20% solution of ammonium persulphate in water.	Swab on freshly made solution for ½ min. Surface B.	Shows fiber and grain contrast.
Flow lines	25% sulphuric acid in water.	Use cold, 8-16 hr. Surface B.	Shows flow lines and dendritic pattern.
Flow lines	50% hydrochloric acid in water.	Use at 160-175°F. Surface A.	Shows flow lines.
Ghost lines	10-20% solution of ammonium persulphate in water.	Swab on freshly made solution for ½ min. Surface C.	Shows ghost lines.

Purpose	Composition	Remarks	Uses
Grain contrast	10-20% solution ammonium persulphate in water.	Swab on freshly made solution for 1-2 min. Surface B.	Shows grain contrast and fiber.
Grain contrast	1.5 g. cupric chloride; 30 cc. hydrochloric acid; 95 cc. water; 30 cc. ethyl alcohol.	Polish specimen carefully. Surface C.	Shows good grain contrast.
Grain size	10-20% solution ammonium persulphate in water.	Swab on freshly made solution for 1-2 min. Surface B.	Shows grain size especially in low carbon steels, wrought iron, and welded sections.
Hardness penetration	5% nitric acid in alcohol.	Etch at room temperature on smooth ground surface. Surface B.	Shows depth of hardness penetration of heat treated samples.
Hardness penetration	50% hydrochloric acid in water.	Use at 160-175°F. for about 15-60 sec. To preserve surface after etching, scrub in running water, dip in weak NH_4OH , dip in solution of soluble cutting oil, dry with a rag and compressed air. Surface B or C.	Shows depth of hardening, especially carbon steels; produces distinct contrast between martensitic and troostitic zones.
Heterogeneity	50% hydrochloric acid in water.	Immerse specimen in solution at 160-175°F. from 1/4-1 hr. Surface A.	Shows heterogeneity in general.
Heterogeneity	Undiluted hydrochloric acid.	Use hot (212°F.) Surface A.	Shows heterogeneity in 3-3.5% nickel steels.
Impurities in ferrite	1 g. cupric chloride; 0.5 g. stannous chloride; 30 g. ferric chloride; 30 cc. hydrochloric acid; 500 cc. distilled water; 500 cc. ethyl alcohol.	Etch only well polished surface which has been thoroughly dried. Surface C.	Plates out copper on ferrite containing impurities. Gives a good even etch.
Internal cracks...	50% hydrochloric acid in water.	Use at 160-175°F. for 1/4 hr. or longer. Surface B.	Shows internal cracks or thermal checks.
Inclusions	10% sulphuric acid in water.	Use cold on large sections for 24 hr. Surface B.	Shows inclusions, porosity, pipe, and blowholes.
Inclusions	10-20% sulphuric acid in water.	Use at 160-175°F. Surface B.	Etches sulphide inclusions.
Inclusions	50% hydrochloric acid in water.	Use at 160-175°F. Surface B.	Etches sulphide inclusions.
Pipe and porosity	10% sulphuric acid in water.	Use cold on large sections for 24 hr. Surface B.	Shows pipe, porosity, blowholes, and inclusions.
Pipe and porosity	50% hydrochloric acid in water.	Use at 160-175°F. Surface B.	Shows pipe, porosity, blowholes, and inclusions.
Rail sections.....	9 parts hydrochloric acid; 3 parts sulphuric; 1 part water.	Use at 160-175°F. for 2 hr. Surface A.	Use for etching rail sections.
Segregation	3% solution picric acid in ethyl alcohol.	Etch at room temperature for 4-5 hr. Surface B.	Shows segregation.
Segregation	1 g. picric acid; 1 drop concentrated hydrochloric acid in 25 cc. alcohol.	Use hot. Surface B.	Shows segregation.
Segregation	10-15% solution of nitric acid in water or alcohol.	Etch at room temperature. Surface B.	Shows heavy segregation.
Segregation	5% solution nitric acid in water or alcohol.	Etches within 1/4 hr. Surface is black when etched. Surface B.	Shows segregation in low carbon, low chromium, nickel steels.
Segregation	2-10% solution nitric acid in water.	Etch first with weak acid to remove machine marks and then increase concentration for structure. Surface B.	Shows segregation in ingot sections and large pieces.

Purpose	Composition	Remarks	Uses
Segregation	50% hydrochloric acid in water.	Use at 160-175°F. Surface A.	Shows segregation in ingot sections and large pieces.
Segregation	1 g. cupric chloride; 0.5 g. picric acid; 1.5-2.5 cc. hydrochloric acid; 10 cc. water; 100 cc. ethyl alcohol.	May be used for electrolytic etching. Surface B.	Shows segregation.
Segregation, carbide	2% nitric acid in alcohol. For high speed steel, use 5% nitric acid in alcohol.	Use cold on a polished, longitudinal section. For high speed steel, etch until matrix is darkened. Surface C.	To detect carbide segregations, particularly in high speed steels.
Segregation, carbon and phosphorus	1 part copper ammonium chloride, 12 parts water.	Immerse finely ground, clean sample in solution for 1 min.; wash with water, and rub off copper. Surface C.	Shows phosphorus and carbon segregation.
Segregation, phosphorus	0.5% solution picric acid in water.	Etch at room temperature until staining occurs. Surface C.	Uneven staining represents phosphorus segregation.
Segregation, phosphorus	30 g. ferric chloride; 100 g. hydrochloric acid; 1 g. cupric chloride; 0.5 g. stannous chloride; 1000 cc. water.	Polish as for microscopic work, use etch cold for 10 sec. to 2 min. Surface C.	Shows phosphorus segregation.
Segregation, phosphorus	10 g. cupric chloride; 40 g. magnesium chloride; 20 cc. hydrochloric acid; 1000 cc. ethyl alcohol (Steads No. 1 reagent.)	Dissolve salts in small amount of hot water, then add alcohol. Apply solution to polished surface drop by drop. Surface C.	Areas not coated by copper show phosphorus segregation.
Segregation, phosphorus	5 g. cupric chloride; 4 g. magnesium chloride; 1 cc. hydrochloric acid; 20 cc. water; 100 cc. alcohol. (Steads No. 2.)	Etch for 1 min. Surface C	Shows phosphorus segregation.
Segregation, phosphorus	4 g. cupric chloride; 20 cc. hydrochloric acid; 40 cc. water; 20 cc. ethyl alcohol.	Polish specimen carefully. Surface C.	Shows phosphorus segregation
Segregation, phosphorus	1.5 g. cupric chloride; 5 g. nickel nitrate crystals; 6 g. ferric chloride; 12 cc. water.	Immerse specimen for 90 sec. or more. Surface C.	Shows phosphorus segregation.
Segregation, sulphur	Soak ordinary sensitized photographic silver bromide paper in a 2% solution of sulphuric acid in water. Apply emulsion side of paper to smooth ground, clean sample for a min. or two. Rinse paper, fix in hypo, wash thoroughly.	The brown pattern formed on the paper indicates the relative distribution of sulphides. The darker and heavier the marks, the more sulphur is indicated to be present. Surface B. Best results are obtained only on first or second prints made from a surface.	Shows the distribution of sulphur.
Segregation, sulphide inclusions	10-20% sulphuric acid in water.	Use at 160-175°F. Surface A.	Etches sulphide inclusions.
Soft spots.....	5% nitric acid in alcohol.	Etch at room temperature. Surface B.	Nondestructive test for hardened tools.
Soft spots.....	50% hydrochloric acid in water.	Use cold on ground surface. Surface B.	Shows soft spots.
Strains	90 g. cupric chloride; 120 cc. hydrochloric acid; 100 cc. water.	Copper does not precipitate with this etch. Heat specimen to 400-475°F. for ½ hr., then etch ground surface for 1-3 min. Rub with powdered cupric chloride, then rinse with alcohol. Surface B.	Shows strain lines.
Strains	6 g. cupric chloride; 6 g. ferric chloride; 10 cc. hydrochloric acid; 100 cc. ethyl alcohol.	Heat specimen to 400°F. and immerse ground surface. Surface B.	Shows strain lines.

Purpose	Composition	Remarks	Uses
Strauss test	3% cupric sulphate; 10% sulphuric acid; 87% distilled water.	Specimen $\frac{1}{2} \times 1 \times 4$ in. is sensitized by actual welding, or artificially by heating to 900-1300° F. (generally 1250° F.). Immersed in the boiling cupric sulphate solution for 72 hr. Specimen is then bent 180° around $\frac{1}{2}$ in. pin. Cracking indicates disintegration has taken place due to migration of carbides to grain boundaries. Surface B. (120° fine emery.)	To measure intergranular corrosion of 18-8 corrosion resisting steel.
Structure	25% nitric acid in water.	Etch at room temperature. Surface B.	Shows general structure.
Structure	50% hydrochloric acid in water.	Use at 160-175°F. for at least $\frac{1}{2}$ hr. Surface A.	Shows general structure and defects.
Structure	2 parts concentrated sulphuric acid; 1 part concentrated hydrochloric acid; 3 parts water.	Use at 160-175°F. for at least $\frac{1}{2}$ hr. Surface A.	Shows general structure and defects.
Thermal cracks	50% hydrochloric acid in water.	Use at 160-175°F. for $\frac{1}{2}$ hr. or longer. Surface B.	Shows thermal checks or internal cracks.
Weld examination	50% hydrochloric acid in water.	When testing large sections, the acid may be added by building a dam with paraffin wax around the part to be tested. Surface A.	For testing the soundness of welds.

The balance of the section on macro etching has been divided into several parts, each dealing somewhat in detail with some of the more important applications of macro etching.

Part II

Recommended Practice for a Standard Macro Etch Test for Routine Inspection of Iron and Steel

General—The macro etch test reveals readily and quickly many of the characteristics of steel, but in some instances, further examination by standard testing methods is required to evaluate them properly. The knowledge that a piece of steel is dendritic or contains metallic and nonmetallic segregates is not sufficient evidence in itself on which to base definite conclusions of the properties of the steel. There is real value in the macro etch test when used to separate materials which are obviously defective from those which are not. It is easily made, but requires experience and judgment to interpret the results.

Preparation of Sample—When it is desired to reveal the surface defects, such as seams, laps, and grinding checks, preparation of the sample is frequently unnecessary. If oil or grease is on the surface, it should be removed. Scale on the surface of the material will be removed by the acid, so that the surface defects will become visible, but in order to reveal the internal structure or defects, a section must be prepared by cutting through the metal at a point where inspection is desired. For best results, the samples to be etched should be in a soft condition.

The surface finish of the specimen depends on the etching solution used. A machined surface is recommended as the standard surface finish in this practice. A ground and polished surface is not necessary and in many instances a fairly smooth sawed cut is satisfactory. This latter statement is true for the higher carbon steels and for tool steels in general. On the very soft steels, a machined surface not too coarsely cut or a sawed surface, rough ground to remove all traces of flowed metal is desirable.

Etching Solution—A solution of one part commercial hydrochloric acid and one part water is recommended. This solution has the advantage that it can be heated without change in concentration. The fumes of this mixture are corrosive so that the work is best done under a hood. (A solution consisting of 38% hydrochloric acid, 12% sulphuric acid, and 50% water is finding some use and shows promising

results. It can be used in the same manner as the recommended hydrochloric acid solution. The apparent advantages appear to be a more sharply defined etched pattern and less susceptibility to rusting.)

It is not necessary to throw away the acid after each test, but for the best results a fresh solution should be used for each test.

For containers pyrex glass, porcelain dishes, or corrosion resisting metals can be used. Satisfactory results have been obtained with hydrochloric acid and particularly with sulphuric acid using a lead lined iron pan or wooden tank provided care is exercised in the application of heat. It is felt, however, that a wooden tank is the least satisfactory type of container and its use should be avoided if possible. For heating the solution the method which gives the best temperature control should be preferred.

Temperature of Acid—A temperature of 160°F. is recommended. This temperature gives a vigorous reaction and does not evaporate the solution too rapidly. If the temperature rises much above 175°F., the etching solution tends to lose its selectivity and a reaction with the entire surface occurs rather than at just the localized points of attack as is desired. On the other hand, a solution temperature below 160°F. will usually unnecessarily prolong the etching operation with little gain resulting. The temperature should be determined with a good thermometer.

It is recommended to first clean the specimens and then heat them in hot water to the same temperature as the acid. The specimens are then transferred to the acid bath, which has first been heated to the proper temperature. By so doing it is much easier to control the time element than if the specimens are put into cold acid and brought up to temperature with the solution, and also it is easier to duplicate conditions time after time.

Time of Etching—The time of etching will depend upon the type of steel to be etched. It is extremely important that the time be accurately determined. If the steel is not etched long enough, the sample will not give all of the information desired; if it is etched too long, some of the more delicate details will be masked by the general destruction of the surface.

When the specimens are in a soft condition, the etching periods given in Table I have been found to give good average results.

Table I
Recommended Etching Time for Various Steels

Steels	Time in Min.	Steels	Time in Min.
S.A.E. Carbon Steels			
1010	15	3140	45
1015	15	X3140	45
X1015	15	3145	45
1020	15	3150	45
X1020	15	3215	45
1025	30	3220	45
X1025	30	3230	45
1030	30	3240	45
1035	30	3245	45
1040	30	3250	45
X1040	30	3312	60
1045	45	3325	60
X1045	45	3335	60
1050	45	3340	60
X1050	45	3415	45
1055	45	3435	45
X1055	45	3450	45
1060	45	S.A.E. Tungsten Steels	
1065	45	71360	45
X1065	45	71680	45
1070	45	7260	45
1075	45	S.A.E. Silicon-Manganese Steels	
1080	45	9255	30
1085	45	9260	30
1090	45	S.A.E. Free Cutting Steels	
1095	45		
S.A.E. Nickel-Chromium Steels		X1314	30
3115	45	X1315	30
3120	45	X1330	30
3125	45	X1335	30
3130	45	X1340	30
3135	45		

(Continued)

Recommended Etching Time for Various Steels—Cont.

Steels	Time in Min.	Steels	Time in Min.
S.A.E. Manganese Steels		S.A.E. Chromium Steels	
T1330	30	5120	30
T1335	30	5140	30
T1340	30	5150	30
T1345	30	52100	45
T1350	30		
S.A.E. Nickel Steels		S.A.E. Chromium-Vanadium Steels	
2015	30	6115	45
2115	30	6120	45
2315	30	6125	45
2320	30	6130	45
2330	30	6135	45
2335	30	6140	45
2340	30	6145	45
2345	30	6150	45
2350	30	6195	45
2515	30		
S.A.E. Molybdenum Steels		Stainless Iron and Steel	
4130	45	Chromium type	30
X4130	45	Cr-Ni type	45
4135	45		
4140	45	Free Machining	
4150	45	Chromium type	30
4340	45	Cr-Ni type	20
4345	45		
4615	45	Tool Steels	
4620	45	Carbon and Carbon-Vanadium	30
4640	45	Manganese oil hardening	20
4815	45	Fast Finishing	45
4820	45	Tungsten hot die steel	45
		Chromium hot-working die	45
		High-Carbon-High-Chromium	45
		High Speed	45

Washing and Preserving Specimens—After the sample is etched, it should be removed from the hot acid and washed under running water, and the "smut" deposited on the specimen should be removed by scrubbing with a stiff brush. Live steam is also an excellent method of washing etched work. The piece is first thoroughly rinsed and placed under the live steam nozzle. This results in rapid and complete drying with freedom from rust. For drying the specimen after washing, it can be blotted with a cloth or paper towel or dried with a blower.

As a simple means of avoiding rusting temporarily, the specimen may be rinsed in water to remove the acid, dipped in ammonia and washed in hot water. For longer preservation, after the specimen has been dried, it should be covered with a thin coat of transparent lacquer, or a film of oil which may be applied with the palm of the hand.

Rusting may be delayed temporarily and mild rusting may be removed by the application to a dried sample of a solution of 50-50 syrup of phosphoric acid to which a little sugar has been added. The excess solution applied may be blotted up with a cloth or paper towels. Caution is recommended in the use of this solution as it will roughen the hands and disintegrate cloth, if allowed to remain in contact an extended time.

Interpretation of Results—The results obtained on properly etched samples are of great value if correctly interpreted. Surface seams, internal cracks, and pipe are easily recognized. It is the improper interpretation of the evidences of segregation and dendritic structures as revealed by deep etching that furnishes the greatest possibility of expensive errors and the needless rejection of material. *It is not true, moreover, that every pit developed indicates the occurrence of an inclusion, since pitting may also occur as a result of acid attack around carbide particles.*

Cracks from Etching—Hardened or otherwise highly stressed steels should be sufficiently tempered before etching to prevent cracking, since otherwise sound steel may crack in the etching solution and thus lead to false conclusions (Fig. 10, page 655).

Grinding Cracks—Grinding cracks can be easily distinguished by the standard macro etch test and are usually identified by a pattern of some symmetry (Fig. 25,

page 658). Again it is emphasized that hardened pieces should be softened prior to hot etching.

Surface Cracks—Surface cracks as revealed by deep etching usually follow an irregular path and may result from improper handling during heating, forging, rolling, or during cooling from the finishing temperature. With heat treated material, surface cracks may be caused by improper treatment, by improper grinding after hardening, or by service stresses.

Seams—Seams in rolled material are of varying depth and usually extend in a straight path parallel to the direction of rolling. With forged material, seams generally follow the contour of the forging and the flow of the metal. The most detrimental result of the presence of seams is their tendency to start fatigue failures, or to open up into deep hardening cracks if the metal is heat treated. This detrimental effect is avoided if, in the manufacturing operations, the surface is machined to a sufficient depth to remove the seams.

Surface Appearance—Steels may etch with a comparatively smooth surface or with a highly rough or pitted surface, depending upon variables in manufacture, and composition. Therefore, a highly roughened surface is not necessarily detrimental (Fig. 11, page 655). It has been found that smoother surfaces can be obtained by adding several drops of organic inhibitor, namely, triamylamine, to the hot etching solution. Inclusions are then attacked in preference to the metal, thereby eliminating the general roughness and consequently producing better patterns.

Irregularity in pitting may usually be attributed to one or more of the defects given below. Certain manganese, oil hardening types are more readily attacked by the acid and are often decidedly roughened without in any way being defective.

Center Porosity—Porosity may be the result of an actual discontinuity within the metal, in which case it is probably more proper to classify the defect as a pipe. Usually, however, the porosity is of such a nature that it is not visible until the specimen has been subjected to the etch. This condition can be found in widely varying degrees and the question of whether the steel should or should not be used is one of experienced judgment (Fig. 12, page 655).

Pipes and Bursts—Pipes are internal cavities formed during ingot solidification and carried through the various manufacturing processes to the finished product. Pipe is invariably associated with segregated impurities which are deeply attacked by the etching reagent. Cavities in the center not associated with deeply attacked impurities are often mistaken for pipe but such cavities can usually be traced to bursts caused from improper handling of the steel during forging or rolling. Either of these defects should be visible after deep etching, and can generally be distinguished from each other by the degree of sponginess surrounding the defect. Piped material usually shows considerably more sponginess than burst material (See Fig. 13 and 14, page 655).

Unsound Steel—Numerous blow holes and nonmetallic inclusions visible as the result of the deep etch are usually indicative of both gases and oxides being distributed throughout the steel at the time casting (Fig. 15, page 655).

Nonmetallic Inclusions and Metallic Segregates—Nonmetallic inclusions usually appear as pits and must not be confused with pits occurring from the etching out of metallic segregates. When nonmetallic inclusions are suspected in highly alloyed steels which may contain metallic segregates, a comparison should be made of an annealed specimen and a hardened specimen etched alike. If the etching pits are the result of nonmetallic inclusions, they will appear similarly in both the annealed and hardened specimens; if they are the result of a metallic segregate they will differ.

Segregations are revealed by the severity of the acid attack on the affected areas. The segregations may occur at the center and be so deeply attacked after etching that they may appear as a pipe, or the segregation may be grouped in some fairly regular form about the center, depending on the shape of the ingot and the mechanical work that has been done upon it.

Segregation as revealed by macro etching is not always an indication of defective material. The segregation revealed by macro etching can be identified by examining a polished specimen under the microscope to determine if it is metallic segregation, crystalline arrangement, or a concentration of impurities. The microscopic identification of segregation may also be supplemented by chemical means; such as analysis of center drillings for carbon, phosphorus and sulphur, or by analysis of inclusions after chemical extraction of same.

Internal Cracks—Internal cracks, sometimes called flakes, cooling cracks, or thermal checks, can be detected by the macro etch test and their identity can be

verified by a fracture test of a hardened specimen on which they are revealed as brightly crystalline spots. These cracks are an actual discontinuity in the metal and, depending on their nature and distribution, may make the steel unfit for use unless they are removed by further hot reduction (Fig. 16, page 655).

Dendritic Pattern—Etching often reveals a dendritic structure which is the result of the crystallization characteristics of the ingot. Dendritic patterns are detected even in steel that has been subjected to repeated mechanical reduction. It has not been proven that dendritic patterns are associated with service failures, provided the material has been subjected to sufficient mechanical working and provided the segregation accompanying the dendritic formation is not in the form of nonmetallic inclusions which are incapable of dispersion.

In the formation of dendrite crystals, the intercrystalline material contains minute metallic segregations which are largely diffused into the crystals. However, when nonmetallic inclusions are thus segregated, they are incapable of diffusion. The use of the microscope is suggested in such cases to supplement the macro examination (Fig. 17, page 655).

Pattern Effect—Pattern effect is almost wholly the result of the crystallization of the ingot and generally results from that part of the bar which was the columnar structure of the ingot etching differently from that part which was the granular structure of the ingot. Should the steel contain considerable sulphide and silicate inclusions, then the area of contact between the columnar structure and the granular structure may be particularly noticeable. In the absence of large amounts of sulphides and silicates, the pattern effect probably is of no serious consequence (See Fig. 18, page 656).

Grain Size—While the deep etch test is of no definite value in determining grain size, nevertheless the manner in which many specimens etch may indicate something of the grain size. Generally the larger the grain, the coarser will be the appearance of the etched surface (Fig. 19, page 656).

Decarburization and Carburization—Generally the areas which have been either decarburized or carburized will etch differently from the remainder of the specimen, chief difference usually being one of color. Decarburized parts will appear lighter in color and carburized parts darker (Fig. 20 and 21, page 656).

If the section to be examined is small enough, it can be given a polished finish and then cold etched, say from 5 to 30 seconds, in nital (3% HNO₃—97% ethyl alcohol). This will generally result in excellent contrast and if the polish is good enough, the same sample can be examined microscopically as well as visually.

Part III

Etching to Determine Penetration of Hardness and Soft Spots—There is a contrast in color, after etching, between the hardened (case) and the unhardened (core) sections of a heat treated section of shallow hardening steel. Use of this characteristic is quite valuable in determining the depth to which a sample has hardened.

To properly show up the penetration of hardness, the sample should have a finish equivalent to that produced by polishing with #00 emery cloth, or finer. The sample can then be etched either in hot or in cold acid. If hot acid, the ground sample is dipped from 15-60 seconds in solution of 50% hydrochloric acid in water at 160-175°F. If it is desired to etch cold, the ground sample is etched from 5-10 minutes in a cold solution 10% nitric acid in water. On a polished surface, nital produces excellent results. After either method of etching, the sample should be thoroughly washed in warm water with a cloth or sponge, and then dried with an air blast. If it is desired to preserve the etched surface of the specimen, the procedure for this, as suggested in Part II, should be followed (Fig. 21, page 656).

Soft spots which so often result when hardening carbon or low alloy tool steels can generally be distinguished by either of the above mentioned macro etching methods. The soft spots invariably etch in relief and are not so dark in color as the harder surrounding areas (Fig. 24, page 658).

Part IV

Etching to Reveal Flow Lines—A longitudinal section when subjected to macro etching will show, to a greater or less degree, flow lines due to the elongation of structural constituents. These flow lines indicate the directions in which the steel was worked during rolling or forging and do not signify defective material (Fig. 2).

The longitudinal face on which it is desired to develop the flow lines should have a smooth surface, either machined or ground. The etching procedure is carried out in 50% hydrochloric acid in water at 160-175°F. in the same manner as outlined in Part II. The length of time required to develop flow lines is a variable, therefore it is necessary to inspect the piece from time to time while it is etching in order to determine when the etch has progressed far enough.

Occasionally a piece will be encountered on which it is difficult to develop flow lines. A suggested aid is to paint the etched surface of the piece with India ink, and then when dry to lightly rub the inked surface with fine emery cloth. This removes the ink from the high portions of the surface and leaves the "valleys" blackened, thus providing the necessary contrast needed to show up flow lines.

Etched surfaces showing flow lines can be preserved in the same manner as other etched surfaces as noted in Part II.

The Significance and Interpretation of Nonmetallic Inclusions in Steel*

Introduction—The inclusions under discussion are the solid, nonmetallic particles present in steel. Gas bubbles and separated carbides are not included. The solid inclusions are primarily oxides, silicates, and sulphides. Some nitrides are included in this category. Few, if any, inclusions are pure chemical compounds, practically all are complex mixtures.

Source of Inclusions—Inclusions may come from the solid products of necessary reactions of the refining process, this type being "natural" inclusions, and normally are quite small, since they are the ones that have not floated out while the steel was still molten or were precipitated during freezing. Accidental or adventitious inclusions are produced by such things as slag mechanically entangled in pouring, eroded nozzle material, pieces of runner bricks, or molding sand. These inclusions get into the steel so late that they do not have time to escape before the steel solidifies. The natural inclusions may be present as a separate phase in the melt at high temperatures, or may be thrown out of solution from the melt because of changing equilibrium conditions and solubility as the temperature falls and the steel freezes.

Effect of Inclusions in Steel—All steel contains some inclusions. Some steels contain many, and among these, the predominant inclusions may be of different types.

Since an absolutely clean steel is commercially unattainable, one must use steel with some inclusion content. Free machining steels with a large content of inclusions of a selected type (mostly sulphides) fill an extremely important place. It is probable that such steels have lowered endurance values and some designers frown on the use of free machining steels for parts to carry load involving impact or repeated stress. It is true, nevertheless, that some types of high sulphur steel have been used successfully in numerous applications where service conditions are severe, as for example, rifle barrels and certain auto parts.

Moore¹ states that dirty steel is unreliable. Moore and Kommers² made endurance tests on annealed screw stock. Some specimens withstood 60 million cycles at 28,000–29,000 psi., but one broke after some 3 million cycles at 25,000 psi.

McAdam,³ Mathews,⁴ and Haigh⁵ comment on low endurance values due to inclusions. It is evident that an inclusion of such shape, nature, and orientation to the applied stress that it will act as an important stress-raiser, analogous to a surface notch, may have a harmful effect, especially in dynamic loading.

Johnson⁶ made endurance tests on aircraft engine steels and found the values to vary inversely with the inclusion count. The small well scattered inclusions had a negligible effect whereas the long stringer type were potent in lowering endurance values.

In static tests the effect of inclusions depends especially on the orientation of the inclusion and the applied stress. A rounded inclusion in cast steel does not have a directional effect on ductility, but elongated ones in wrought steel may cause the transverse ductility to fall markedly below the longitudinal ductility, though the tensile and yield strengths are practically unaffected. Wrought iron, with its slag stringers, is a notable example of a metal with directional properties caused by inclusions.

Effect on Mechanical Properties—That inclusions never exert any harmful effect on mechanical properties is a thesis that could not be defended. It is often extremely difficult, however, to establish that inclusions are harmful. For example, the Joint Committee on Effect of Sulphur and Phosphorus in Steel⁷ carried out exhaustive tensile, shear impact, and endurance tests on rivet steel, with S varying from 0.03–0.18% and hence, in the higher S steels, with copious inclusions of the MnS type. The sum total of all these tests was that the properties of rivet steels were practically unaffected by the inclusion content, except in respect to notch bar impact values. These were, of course, soft plastic steels in which redistribution of

*Prepared by the Subcommittee on the Significance and Interpretation of Nonmetallic Inclusions. The membership of the subcommittee was as follows: Clyde E. Williams, Chairman; C. H. Herty, Jr., John Chipman, D. J. McAdam, Jr., Merrill Schell, C. E. Sims, E. C. Smith, S. F. Urban, A. L. Boegehold, H. W. Graham, J. B. Johnson, L. A. Lanning, B. M. Larsen, G. C. Riegel, Frank Scott, F. N. Speller, Haakon Styrl.

stress takes place readily. This may account for the minor effect of the MnS inclusions.

The distribution of inclusions may profoundly influence their effect on the mechanical properties of steel. This has been clearly demonstrated for cast steel by Sims² and Lillieqvist who showed that sulphide inclusions when present as widely separated globules had a minimum effect on ductility and notch bar impact values, but when they are strung out in the primary grain boundaries as films or eutectic formations, they may drastically lower these properties.

Certain Types of Inclusions May Be Beneficial—It is generally considered that a steel to which aluminum has been added for purposes of grain size control contains Al_2O_3 inclusions or complex inclusions largely made up of Al_2O_3 , even though we cannot see them under a microscope. Whether one wishes to consider Al_2O_3 or residual Al as the primary cause of inhibition of grain growth, few will dispute that Al_2O_3 is present. In this case, however, it is almost certainly the submicroscopic and not the visible particles which restrict the grain growth. Bain³ commented on the exaggerated grain growth and propensity toward hardening cracks of very pure Fe-C alloys and remarked that where it is necessary to handle such material commercially, one would have to add judiciously selected nonmetallic material to make it fit for service. On the other hand, clumps of Al_2O_3 , visible to the unaided eye are known to be deleterious to tool life in machining and to dies in wire drawing.

Nonmetallic particles of sufficient number and of submicroscopic size may have a marked strengthening effect on mechanical properties, but, especially if the matrix is ductile and if the particles are rounded, the same materials agglomerated to the size of the smaller inclusions that we can see under the microscope, have much less effect. This is evident in the difference in properties of two precipitation-hardening alloys, one of which is fully hardened and the other over aged so that the hardening particles were agglomerated.

Inclusion Rating Charts—For any particular service, between the unattainable lower limit of a steel with no inclusions at all and the upper limit of a steel so dirty as to be admittedly unsuitable, there is some not well defined region that divides the acceptable steels from the unacceptable. For a long time, producers and users have attempted to precisely define this region, and to find methods for definitely specifying the limiting content, size, type, and distribution of permissible inclusions.

These attempts usually take the form of "inclusion" charts or numerical ratings derived from the charts, showing unetched micrographs with characteristic inclusions as to size, shape and frequency of occurrence. The specimen, selected from a predetermined position in the bar or billet, is rated by the comparison with the chart. There is no unanimity in the standard charts, each large purchaser is likely to have his own, and each steel mill may, in addition, have its own chart. However, the charts do not vary enough to make it important which particular one should be adopted when the time comes to standardize some more official method of rating.

The difficulty in the use of any chart lies, not in telling what standard micrograph or micrographs match the inclusions in the specimen being examined, but in knowing that the specimen is a representative sample. A large number of sections must be examined in order to establish on a statistical basis what the correct rating of the steel may be. Apparent uniformity in the specimens examined, moreover, does not prove that the steel does not have some large or segregated inclusions in some other part of the heat. With sufficient patience almost any one who wished to reject a lot of steel could find some single field under the microscope containing sufficient inclusions to appear to justify a claim that the steel was not of proper quality, although this field might represent only the minutest area of the whole lot of steel under consideration.

By their very nature, inclusions are not homogeneously distributed through the steel, so that random sampling may entirely fail to appraise the steel as a whole.

Chance plays an important part in the distribution of inclusions, and likewise in the location of an inclusion at a point of crucial stress in an actual structure. For example, it is by no means uncommon, in examining a rotating beam endurance specimen which has shown normal life, to find a few hundredths of an inch away from the most highly stressed area of the surface, an inclusion which, had it lain in that most highly stressed area, would have led to early failure, but because it was not situated at the unfavorable location, did no harm whatever. Likewise, large inclusions elongated in the direction of the stress often have an insignificant effect.

Poor fillets, tool marks, key ways, stamped numbers, accidental scratches and

similar imposed stress-raisers, cause a thousand failures to one that is properly ascribable to a stress-raising inclusion in the metal itself. Yet, in some uses, such as automotive and aircraft ordnance, and in pressure vessel applications, it is important to eliminate the possibility of the one failure due to an inclusion.

One would expect a close correlation between inclusion content and performance in hard, highly stressed balls, rollers, and races of antifriction bearings. Steels containing large inclusions, visible to the naked eye on a polished surface, have been found to be subject to flaking and spalling, and many fatigue failures in large roller bearings have been definitely shown to have their origin in slag stringers so large that they must have been of accidental or adventitious origin. Little definite relation has been found between bearing life and presence of the normal inclusions of microscopic size. The opinion is held by some bearing manufacturers, nevertheless, that even small inclusions are harmful in very hard steels.

It is chiefly in the case of impact or repeated stress that the accidental stress-raising inclusion is to be feared in otherwise satisfactory material. The problems of directional ductility in deep drawing, cold bending, flanging and similar operations where breakage might occur in fabrication are easily handled by transverse bend and tensile tests in standard mechanical testing, and the inclusion problem is not of direct importance from the point of view of such fabrication. Inclusions might be the last straw to render material otherwise somewhat lacking in suitability obviously unsuitable, but will seldom indeed be a major cause. Steel for quenching may be more prone to quenching cracks because of inclusions, but this again is seldom a major cause of trouble, other factors usually being far more potent.

From the point of view of mechanical failure inclusions met in ordinary commercial steels may be said to have practically no deleterious effect in parts made of ductile material, subjected to static stress. Under applied stress such material is deformed plastically at the apex of the stress-raiser, the stress is redistributed, and nothing further happens. As the matrix becomes harder, through increase in carbon or alloy content, and still more markedly when hardened by excessive cold work or by quenching, followed by only a limited toughening by tempering, as in spring steel, the effect of an imposed stress-raiser is more marked, even in static loading, and still more marked in impact or under repeated stress. The effect of a stress-raising inclusion is analogous to that of an imposed stress-raiser. Hence, inclusions may be expected to have little effect in soft steels under static load, as in structural steel for buildings, but an important effect in very hard steels under dynamic loading.

To impose the same inclusion ratings on reinforcing bar and on airplane connecting rods would be poor engineering. Yet it is difficult for the engineer to determine the proper inclusion rating for an automobile gear steel, and wide differences of opinion exist.

Inclusions May Be Detrimental in Welds—In this case again it is the gross inclusions that are most feared. Slag reaction products have very little time to rise in the short time the weld metal is fluid. Welding rods coated with, or containing, materials that produce a blanket of reducing gas to exclude oxygen and nitrogen of the air, and others that produce very fluid slags with the oxygen contained in the air that reaches the weld, as well as processes of welding under layer of fluid slag, are employed to avoid weld defects arising from inclusions. These large inclusions are generally detectable by radiography so that specific inspection methods are available through which to trace down and eliminate the causes of trouble.

The suitability of steel for welding and for use in welding rods may be affected by gas evolution resulting from reaction of carbon with oxygen in oxide or silicate inclusions, which gas may cause splatter. Inclusions of MnS are reported to exhibit profound effects at the temperatures used in welding. Direct tests are, of course, available to handle such problems.

There are cases in which there is no fear of inclusions directly on the score of strength, but where they may nevertheless injure the suitability of steel. Objects that are given a high polish may have poor appearance due to the presence of large inclusions in the polished surface. In some instances embedded particles of the polishing medium have been mistaken for inclusions. Metal plated on a surface carrying inclusions may not adhere at the locations of the inclusions. Direct tests as to the specific effect may be applied in such cases.

The Effect of Inclusions on Corrosion Is in Dispute—It is alleged for wrought iron that the inclusions improve the corrosion resistance while in stainless steel they have been termed definitely harmful. There is not enough difference in the corrosion rate of wrought iron and mild steel to warrant the conclusion that the

presence of inclusions has any effect. As far as the great tonnage of steel is concerned, corrosion resistance is a secondary factor and inclusions cannot change its order of magnitude.

Sulphide inclusions on polished surfaces are sometimes thought to tend to localize corrosive attack. Most other inclusions are so resistant to solution by water that they appear quite inert in respect to either atmospheric or submerged corrosion. On the whole, normal variations in the corrosive environment have far more influence than variations in inclusion content.

The effect of inclusions on machinability and tool life is not very clear. Very clean steels, by the usual inclusion rating, may behave worse than a very dirty steel and the free cutting steels intentionally carry large amounts of sulphide, selenide or other relatively soft inclusions. It is not yet definitely settled as to whether these inclusions have a direct or corollary effect on machinability, and the speed at which such steels can be cut is not necessarily in the order of the amount of visible inclusions present. It may well be that inclusions of submicroscopic size have as much effect on machinability as larger ones. Steels so finished as to contain any free Al_2O_3 are not considered ideal for good tool life. Very large inclusions, even of softer materials, may cause the tool tip to chip.

Here again, specific tests, made under service conditions are better criteria than any ordinary inclusion rating.

General Considerations—Considering the inclusion problem as a whole, the very large, accidental inclusions of the type produced by eroded nozzle, runner brick or other foreign matter that gets into the steel so late that it is caught instead of rising out of the steel, are universally considered detrimental. It is an impossible task certainly to detect such an adventitious inclusion, since there might be but one in an ingot and every possible sample, other than that right at this inclusion, will give no hint of its presence. Avoidance by scrupulous cleanliness and adequate cropping, rather than testing, must be the remedy for such cases.

In general, any inclusion larger than the size corresponding to 0.01 inch diameter before the steel is worked, may be suspected of being adventitious.

The smaller natural inclusions tend to be more uniformly distributed through the steel, but segregation occurs during freezing, and this segregation is affected by many variables so that there is little assurance that a sample from any one location in the ingot will tell definitely the inclusion content at other locations.

The necessity for systematic sampling in making inclusion counts under the microscope has been stressed by Epstein.¹⁰ A random sample on a bar whose location in the ingot is not known stands little chance of appraising all the steel from that ingot and still less, all from that heat.

From the point of view of mechanical properties of steel containing inclusions, one is interested in the composition and nature, shape and distribution of the inclusions. This phase of the subject is discussed in other sections of the Handbook and may be referred to for details.

Inasmuch as the methods for determination of the inclusion rating of a steel are so difficult and time consuming, and generally so unreliable (because of defects in the methods and especially because of difficulties in sampling) it is not remarkable that few clear-cut conclusions can be drawn as to the exact effect of inclusions. It is plain that the most dangerous inclusions are the large ones that get in by accident, and that determination as to whether such inclusions exist in a given lot of steel is a difficult if not an impossible matter. The experience of industry, however, has indicated that within certain broad qualitative limits more consistent and uniform performance may be expected in dynamic service from those steels which contain a minimum of nonmetallic inclusions. This conclusion has led to a great amount of study and effort to produce cleaner steels and there is no doubt that this work has resulted in a lower average inclusion content for high grade steels.

It seems certain that nonmetallic inclusions have their greatest significance for the steel plant metallurgist, because they so often furnish excellent circumstantial evidence for the diagnosis of pathological conditions. This phase, of course, is more concerned with identification and distribution than with quantity and inasmuch as its ramifications lead deeply into the field of process metallurgy, it is outside the province of this article.

In regard to serviceability, the deleterious effect of the microscopic, normal inclusions of carefully made steel has probably been over emphasized. Some large users of steel for dynamic service consider the test for microcleanliness the least

significant of all the tests used for acceptance of steel. While it is true that inclusions have been identified as the direct or contributory cause of some failures, in most failures in service it is wise to look for other plausible causes for trouble, before worrying about the probable effect of an occasional inclusion.

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Identification of Inclusions in Steel by the Use of Reflected Polarized Light*

Introduction—The use of reflected polarized light is a comparatively new tool in metallography. Transmitted polarized light has been used for some time to determine strain in transparent substances (photoelasticity). The use of polarized light to determine the constituents of mineralogical thin sections is well known and in technological practice. The science of mineralogy has thus far described 261 minerals as opaque, of which 93 are shown by the microscope to be either mixtures of minerals or doubtful species.¹ The use of a polarizing microscope is no longer confined to the field of petrography. Due to the pioneer work of Dr. Emile Chamot, the polarizing microscope is now used to advantage in the field of chemical microscopy.² Slag investigations have been carried out and the mineral composition determined with the aid of the polarizing microscope.^{3, 4} Research workers in various branches of science have given testimony to the possibilities of investigation with this tool. Although the use of polarized light was recommended for the study of opaque substances as early as 1909 by Königsberger,⁵ it has not been used in metallography until quite recently. A few treatises have appeared from time to time dealing with reflected polarized light in the study of opaque ores and metals (See references 6-18).

The use of reflected polarized light to identify opaque substances has not been as outstanding as the effects obtained with transparent materials. Until quite recently all of the polarizing microscopes for reflected light did not furnish truly linear but slightly elliptically polarized light in the plane of the object.⁶ The amount of this elliptical polarization was small but in some cases was sufficient to produce abnormal extinction effects. In recent years the vertical illuminator has been much improved in the homogenization of the field for observations between crossed nicols and improvements in this direction are being continued.^{7, 8}

During the past six to seven years efforts have been made by various investigators to apply polarized light to metallography, as a further means of identifying inclusions, structural components and phases. In the development of what is practically a new branch of science, it is not surprising that the results obtained by earlier investigators were not always in agreement. The investigations that have been reported show the utility of polarized light in the study of nonmetallic inclusions (See references 19-31).

During the evolution of this new tool, for metallographic investigation, research workers have realized that certain limitations must be placed upon its use in order to arrive at the correct interpretation of the results given. In order that the investigator shall not obtain an erroneous identification of the inclusions to be studied, he should have in mind these limitations before attempting to make full use of reflected polarized light. He should also realize that this method, of itself, is often not conclusive and therefore should be used with the aid of other methods of identification such as etching. The nature of the optical phenomena observed is dependent, to a significant extent, on the design of the optical system.

Polishing the Inclusions for Microscopic Examination—The preparation of the sample for the study of inclusions is of great importance to the success of the examination. There are several good methods of preparing the surface, and any method of polishing which gives the following results should be entirely satisfactory: (1) A smooth and level metal surface; (2) retention of inclusions; and (3) a satisfactory polish on the surface of the inclusions, free from scratches, distorted surface layers, and films.

The sample for examination of inclusions may be mounted in bakelite or hard resin to facilitate hand polishing or automatic polishing of small specimens. The usual preliminary polishing steps are employed, such as coarse grinding and fine grinding on the metallographic dry papers No. 1, 0, 00 and 000. Frequently, used 000 paper rubbed over with paraffin or graphite is employed. The use of graphite is cautioned against, at least for inexperienced polishers, as this practice frequently leads to embedded graphite in the surface layers of metal during polishing. Such embedded graphite, after final polishing with alumina or magnesia, may have the appearance of an inclusion.

*Prepared by a subcommittee, the membership of which was as follows: Merrill A. Scheil, Chairman; Mary Baeyerztz, and Joseph R. Vilella.

The final polishing is carried out on broadcloth laps using levigated alumina or magnesia. After final polishing it is important to properly clean and dry the prepared surface. Dried water spots produce bright areas under crossed nicols, and clumps of the polishing media or dirt tend to sparkle on the otherwise opaque polished surface, and may lead to erroneous conclusions. It is not advisable to etch the prepared polished surface before microexamination, with polarized light, because the surface roughness produced by etching causes scattering reflections which are confusing and may lead to grating polarization. Heat tinted specimens should not be used since such treatment may cause oxide films on the surface of the inclusions.

Method of Examination—After proper preparation of the polished surface the section is first thoroughly examined under ordinary reflected white light to determine the size, shape, color by ordinary reflected light, and distribution of the inclusions. The section is then examined with reflected plane polarized light with nicols crossed. Two determinations are made, namely, the determination of the color by transmitted light and the examination for evidence of anisotropic behavior.

Path of the Rays in Microscopes for Use With Reflected Plane Polarized Light—The examination of inclusions with reflected plane polarized light may be made with the usual types of metallurgical microscope, if accessory equipment with which to obtain and analyze the plane polarized light is added, and certain precautions are observed. Some manufacturers now make such equipment in holders especially designed to fit into the optical train of microscopes of their own manufacture.

The usual source of light for a metallurgical microscope is an arc or filament lamp. Light from either of these sources may be considered as vibrating in all directions normal to the light beam. In order to obtain plane polarized light (vibrating in one direction only), it is necessary to interpose a polarizer in the light beam. The polarizer should be situated between the light source and the field stop or aperture stop. The polarizer should always be protected by a heat absorbing glass placed between it and the light, in the case of an arc lamp. With small incandescent lamps this is not necessary.

The polarizer, commonly termed "nicol prism," is so constructed that when a beam of unpolarized light is passed into it, the resulting transmitted beam is plane polarized. The vibration direction of the light emerging from the polarizer can be regulated by rotating the polarizer around the axis of the optical train. The polarizer should be rotated until its vibration direction is either perpendicular or parallel to the axis of tilting of the reflector in the vertical illuminator and then be kept in that position during microscopic observations. If the polarizer deviates only a fraction of a degree from this position, elliptical polarization will be introduced.

From the vertical illuminator, usually a prism of special design, the plane polarized light is projected through the objective to the specimen surface from which it is reflected into the microscope to the eyepiece which forms the visible image. Before being viewed at the eyepiece, the light reflected from the specimen is passed through an analyser. The analyser may be placed between the vertical illuminator and the eyepiece or a cap nicol, placed over the eyepiece, may be used instead.

The analyser functions in a similar manner as the polarizer. Thus only plane polarized light which vibrates in the direction of the analyser can pass through it. When the vibration direction of the analyser is set at 90° to the vibration direction of the polarizer, the nicols are said to be "crossed." With crossed nicols the plane polarized light which passes the polarizer, if reflected unchanged to the analyser, cannot pass the analyser and the field of view is dark. If the character of the polarization is altered, that is, if the plane polarized light becomes elliptically polarized, or the vibration direction of the polarized light is changed then light will pass the analyser.

Change in the character of polarization and resolution into components of the vibration direction of plane polarized light can be caused by reflecting surfaces in the optical train, so it is advisable to eliminate them or place them so that the minimum effect is obtained. Rotation of the specimen should be obtained by rotating the stage on which the specimen is fixed. For this purpose the microscope should be equipped with a rotatable stage, preferably graduated in degrees. Cross haired eyepieces, representing planes of vibration of the nicols, are very desirable.

Brightness, Color, and Surface Anomalies—Brightness or transmitted light color may usually be observed in a few inclusions if a number are present and if the inclusions are transparent or reasonably translucent.

The transmitted light is observed because incident plane polarized light is refracted into and transmitted through the translucent inclusions and is reflected from the inclusion metal interface, from a crack in the inclusion upon which back reflections can take place, or, in inclusions which contain more than one phase, from the phase boundaries within the inclusion. The light coming out from the inclusion is no longer plane polarized as it was before entering the inclusion. Random reflections from the inclusion metal interface and other internal interfaces cause the character of original plane polarized light to be changed so that light passes the analyzer. This effect has no connection with anisotropism (both isotropic and anisotropic substances show it) and particular care should be taken not to confuse it with anisotropic behavior. If the nicols are parallel appearance of the inclusions is similar to that observed by ordinary reflected light. The general illumination from the incident beam as reflected from the polished metal surface is so great that the much weaker transmitted light from the inclusion cannot be observed or is seen only indistinctly. This small amount of light from the internal reflection through the inclusion may be seen by crossing the analyzer nicol, which efficiently removes the surface reflected light and if the inclusion is sufficiently translucent its transmitted color can be identified provided that the birefringence of the inclusion mineral is not high. Under certain conditions of internal reflection in minerals of high birefringence, the colors observed with crossed nicols are interference colors rather than the transmitted light color of the mineral. If the substance is translucent the transmitted light color may be complicated, with certain anisotropic inclusions, by reason of high absorption for certain wave lengths which vary in certain crystallographic directions of crystalline inclusions (reflection pleochroism).

Aside from these confusing effects in certain anisotropic inclusions, the determination of the transmitted light color depends on the following factors: (1) The dimensions of the inclusion; (2) the orientation of the reflecting surface with respect to the vibration planes of the nicols; (3) the translucence of the inclusion; (4) the method of polishing (freedom from polish film, scratches, and differences in level of different constituents); (5) the crystallographic orientation of any anisotropic crystals in the inclusion from which internal reflection takes place; and (6) the numerical aperture and type of objective.

Thus reflection through a relatively thin layer of a highly translucent substance from a metal inclusion interface or, in inclusions which contain more than one phase, from a highly reflecting phase-translucent phase interface will give the maximum reflected light for observation, provided that the reflecting surface is properly placed with respect to the vibration directions of the nicols. The difficulties of determination of the transmitted light color increase markedly as the translucence of the inclusions decreases. An objective of high numerical aperture sometimes alters the apparent brightness and color of the inclusion regardless of whether it is translucent or opaque. This is probably due to the fact that less of the plane polarized light can be reflected unchanged, because of the possibility of introducing elliptical polarization caused by objectives used for high magnification. The light gathering properties of the high numerical aperture lenses make any particular inclusion, only slightly translucent, appear brighter than with lower numerical aperture lenses. With opaque inclusions, especially, immersion objectives modify the apparent reflectivity. The apparent reflectivity increases as the difference between the refractive index of the inclusion and the refractive index of the surrounding material increases. Portevin and Castro⁸ have observed that examination under a dry objective generally gives more violet shaded colors than an immersion objective does. At times the dimensions of the inclusion and the surface polish offer disturbing effects to a proper identification. In certain hard inclusions of small dimensions, their surface is not always polished plane and is frequently convex. When examined by reflected polarized light, diffraction and depolarization phenomena are set up at the edge of the inclusion. Likewise, pits and scratches on isotropic surfaces improperly prepared can produce effects which may be mistaken for anisotropic behavior.

Anisotropic Behavior—Examination of the inclusions by reflected polarized light between crossed nicols may enable the investigator to distinguish the isotropic

vitreous (no crystal system) and crystalline substances (cubic system) from the anisotropic substances (all other crystalline systems).

Substances showing one index of refraction are called isotropic and regardless of their orientation they appear to have no effect upon the light which enters them, other than single refraction and the absorption giving rise to their transmitted light color. Examples of isotropic substances are those which crystallize in the cubic system (including most metals), and those which can be classified as amorphous (glasses).

Anisotropic substances exhibit more than one index of refraction, that is, anisotropic materials possess the property of resolving the vibrations of light which enters them into component vibrations which are plane polarized, but vibrate in different planes and travel at different rates through the crystal. The difference between the indices of the rays gives the strength of birefringence and is characterized as strong or weak. The identification of anisotropy in inclusions of weak birefringence, that are transparent or translucent, is especially difficult owing to the disturbing effects of internal reflection. Thus, materials of weak birefringence appear to behave the same as isotropic ones under reflected plane polarized light with nicols crossed. Opaque isotropic inclusions will remain dark in all positions when the specimen is rotated in the plane of its polished surface, the reason for this being that the plane polarized light suffers no change in its state of polarization when reflected vertically from any plane surface of the isotropic substance. Thus the direction of vibration is unchanged and if the nicols are crossed the reflected light will be extinguished by the analyser.

Anisotropic substances when examined with completely linearly polarized reflected light, disturb the condition of the plane polarized light beam reflected vertically by their surface. These disturbances may show themselves in two ways. Most important of these changes is the resolution into components of the plane of vibration. Due to this resolution into components, the reflected light will have a component in the vibration direction of the analyser and some light will pass through it. Rotation of properly oriented crystals of the anisotropic substance will cause the reflected light to vary from extinction to maximum brightness four times in 360° rotation of the stage, in contrast to opaque isotropic substances which remain dark between crossed nicols as during a 360° rotation. Only in the positions in which the principal directions of vibration (axes of optical elasticity) of the anisotropic surface coincide with the vibration directions of the nicols will there be extinction. At these positions there is no resolution into components of the plane of vibration of the reflected light.

The incoming linear polarized light can also be reflected as circular or elliptical polarized light, two special cases of the resolution into components, which is produced because of the birefringence of the material. These are the principal disturbances which cause a change in the nature of the polarized light if brightness of the beam has been restored. These two effects can be distinguished from one another by means of compensators which can be added between the polarizer and analyser. The function of the compensator is to introduce any desired phase difference into polarized light. A quartz wedge is an example. Thus by means of compensators, polarized light with any amount of ellipticity may be changed to plane polarized light which is the only type of polarized light capable of being entirely absorbed by the analyser nicol.

These disturbances of the plane of vibration can vary in regard to the degree to which they can be evidenced so that we observe a strong or a weak birefringence.

The magnitude of these effects in most cases are rather small, particularly with inclusions exhibiting weak birefringence, so that it is of great importance that the incoming polarized light be wholly plane polarized as otherwise any small elliptical polarization effect from the inclusion may be missed, and the absence of observable anisotropic behavior under crossed nicols will not indicate that the inclusion may be actually isotropic. The effects obtained by internal reflection and anisotropic behavior are superimposed in translucent anisotropic inclusion minerals. A thorough knowledge of the optical system being used, of the behavior of polarized light and also of the optical properties of inclusion minerals is required to interpret microscopic observations.

Identification Tests for Inclusions—The following scheme of identification contains tables of properties of substances which may be encountered as nonmetallic inclusions in the examination of steels and irons. It should be noted that inclusions in metals rarely consist of a single pure component and their properties are there-

fore unlikely to coincide precisely with those of the minerals to which they are related. Further, the methods just described for the examination of polished metallographic specimens are sometimes incapable of distinguishing some of their optical properties. For more detailed information on the minerals given in the tables, and for information on other possible "inclusion minerals," the investigator is referred to E. S. Dana "Textbook of Mineralogy" edited by W. E. Ford, A. N. Winchell "Microscopic Characters of Artificial Minerals," and H. Schneiderhöhn and P. Ramdohr "Lehrbuch der Erzmikroskopie," v. 2.

The minerals described however, will help to identify inclusions on the basis of optical character. Certain inclusions derived from refractories occur as minerals and the use of these tables will help to identify such inclusions which might be identified as other substances if the scheme for etching identification tests were used alone.

The tables also include the characteristics, which may be observed by reflected plane polarized light with crossed nicols, of inclusions in steels and irons similar to the composition of the minerals.

The properties of the minerals described in the tables (a) to (f) inclusive are for minerals of the particular allotropic modification as stated and do not correspond in all cases to the properties of inclusions that may occur in steels and irons of quite similar chemical composition.

For the convenience of the investigator an etching scheme is also included to enable the identification of certain opaque oxides frequently encountered as well as other isotropic substances which can sometimes be identified by their color and shape and can be further distinguished by their etching characteristics.

The investigator should make all of his observations by reflected plane polarized light with crossed nicols, first, before applying the etching tests to his sample for identification purposes.

Proper use of the scheme should employ the following procedure:

1. Examination of the inclusions "as polished" with ordinary reflected white light at X200, X500 or X1000; to observe the size, shape, reflected light color, and distribution of the inclusions.

2. Selection of several representative fields for further investigation by reflected plane polarized light with crossed nicols for observation of isotropic or anisotropic behavior, opaqueness or translucency, and transmitted light color.

3. Complete identification of opaque inclusions and others when in doubt with appropriate etching tests.

A more complete report of this article will appear in Trans. A.S.M.

Distinctions to Be Observed for the Identification of Inclusions in Steels and Irons With Reflected Polarized Light

System Used Below for Property Designation

- | | |
|-----------------------------------|--|
| 1. Name and Formula | |
| a. Crystal system | e. Color by transmitted white light (plane polarized light crossed nicols) |
| b. Melting point | f. Index of refraction |
| c. Hardness (Mohs' Scale) | g. Common occurrence |
| d. Color by reflected white light | h. Remarks |

Inclusion Minerals Which Always Remain Dark During 360° Rotation

- | | |
|--|--|
| 1. Ferrous oxide, FeO | |
| a. Isometric | g. In scale, and as more or less rounded single phase globules in rimming and similar steels low in silicon and manganese. |
| b. 1360°C., 2480°F. | h. Somewhat malleable at S R T (steel rolling temperatures). |
| c. 5.5-6.5 | |
| d. Medium grey | |
| e. Opaque | |
| 2. Magnetite, FeO.Fe ₂ O ₃ | |
| a. Isometric | e. Opaque |
| b. 1327-80°C., 2421-2516°F. | g. In scale |
| c. 5.5-6.5 | h. Not malleable at S R T |
| d. Light grey | |

3 Titanium nitride, TiN

- a. Isometric
- c. 9-10
- d. Yellow
- e. Opaque
- g. In steels and irons treated with ferro-titanium.
- h. Not malleable at S R T. May contain TiC in solid solution. Color in reflected white light varies from yellow to pink to violet with increasing carbon content. Pink sometimes called cyano-nitride. The inclusions are strongly angular and easily pitted in polishing.

4. Zirconium nitride, ZrN

- a. Isometric
- b. 2950°C., 5342°F.
- d. Yellow
- e. Opaque
- g. In steels and irons treated with ferro-zirconium.
- h. Not malleable at S R T. May contain ZrC in solid solution which produces varying colors by reflected white light: Orange, brown, violet, blue. The inclusions are strongly angular and they may be distinguished from TiN by etching tests. They are softer and easier to polish than TiN.

5. Vanadium nitride, VN

- a. Isometric
- b. 2000°C., 3632°F.
- c. 9-10
- d. Pink
- e. Opaque
- g. In vanadium steels. These inclusions resemble titanium cyano-nitride.

*Translucent Isotropic Inclusion Minerals***1. Manganous oxide, manganosite, MnO**

- a. Isometric
- b. 1700°C., 3092°F.
- c. 5-6
- d. Very dark grey
- e. Green
- f. $N = 2.16$ (Li)
- g. In steels and irons high in manganese which have not been deoxidized with other more effective deoxidizers, for example, aluminum and silicon.
- h. Somewhat malleable at S R T. Usually contains more or less FeO in solid solution. Color by reflected white light changes from dark grey to medium grey with increase in FeO. Color by transmitted light changes from green to red or brownish red to opaque with increase in FeO.

2. Manganous sulphide, alabandite, MnS

- a. Isometric
- b. 1620°C., 2948°F.
- c. 3.5-4
- d. Medium grey
- e. Green
- f. $N = 2.70$ (Li)
- g. Steels and irons except those with very low manganese content.
- h. Very slightly malleable at S R T, malleability increases with increase in FeO in solid solution. Usually contains FeS in solid solution. In stainless steels probably also contains Cr in solid solution. Color by reflected white light changes from medium grey to greyish white, with pearly luster, with increase in FeS. Color by transmitted white light changes from green to greenish yellow or brown to opaque with increase in FeS.

3. Iron aluminate, hercynite, $\text{FeO} \cdot \text{Al}_2\text{O}_3$

- a. Isometric
- b. Above 1700°C., 3092°F.
- c. 7.5-8
- d. Medium to dark grey
- e. Colorless, green, yellow brown, reddish brown, opaque when rich in iron oxides.
- f. $N = 1.80$
- g. In steels and irons treated with aluminum and in some inclusions derived from refractories.
- h. Not malleable at S R T. Change in color and translucence due to solid solution. Opaque varieties are lighter grey by reflected white light. Frequently occurs as equiaxed euhedral crystals. Not as difficult to polish as inclusions rich in Al_2O_3 .

4. Chromite, $\text{FeO} \cdot \text{Cr}_2\text{O}_3$

- a. Isometric
- b. 5.5
- d. Medium grey
- e. Red, reddish brown, yellowish brown, or opaque depending on the thickness.
- f. $N = 2.07-2.16$
- g. In steels and irons which contain chromium.
- h. Not malleable at S R T. Frequently occurs as equiaxed euhedral crystals, and also observed to be of eutectic nature. These inclusions are easily polished.

5. Silica glasses

- a. Noncrystalline
- b. Variable
- c. Approximately 7
- d. Light to very dark grey, sometimes with bright internal reflections.
- e. Colorless or all colors depending on contamination with other oxides.
- f. Variable
- g. In steels and irons which contain silicon which have not been thoroughly deoxidized with other more effective deoxidizers, for example, aluminum; and in some inclusions derived from refractories.
- h. Varying degrees of malleability at S R T. May be more or less milky because of precipitation of other minerals in finely divided state within the glass on cooling. In cast or weld metals transparent spherical glassy silicates exhibit the dark optical cross by transmitted white light.

Opaque Minerals Showing Anisotropic Behavior

1. Ferrous sulphide, troilite, FeS

- a. Hexagonal
- b. 1180-1190°C., 2156-74°F.
- c. 3-4
- d. Light tan or yellow
- e. Opaque
- g. In steels and irons very low in manganese
- h. Malleable at S R T. Under reflected plane polarized light with nicols crossed, properly oriented grains show four extinctions in 360°.

*Translucent Anisotropic Minerals with Weak Birefringence*1. Alumina, corundum, Al_2O_3

- a. Hexagonal
- b. 2050°C., 3722°F.
- c. 9
- d. Medium grey
- e. Colorless
- f. $N = 1.77$ Ne = 1.76 (Na)
- g. In steels and irons treated with aluminum, and in some inclusions derived from refractories.
- h. Not malleable at S R T. Color by transmitted light changed variously by impurities in solid solution. Occurs as equiaxed or elongated grains with irregular surfaces, or euhedral crystals.

These have a tendency to group together in clumps or small clouds of particles. During rolling or forging these groups are formed into irregular rows of particles in the direction of working. These inclusions are rarely pure and may contain FeO and SiO_2 . The inclusions rich in Al_2O_3 are difficult to polish and frequently their anisotropic behavior is masked by reason of their transparency and highly reflecting metal inclusion interface, or by rounding the edge of the cavities left by their removal.

2. Mullite, $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$

- a. Orthorhombic
- b. 1816°C., 3301°F.
- c. 7.5
- d. Medium to dark grey

- e. Colorless, pink
- f. $N_g = 1.654$, $N_m = 1.644$, $N_p = 1.642$
- h. Frequently occurs as long euhedral crystals in glass inclusions.

3. Quartz, SiO_2

- a. Hexagonal
- b. 1600-1750°C., 2912-3182°F.
- c. 7

- d. Medium to dark grey
- e. Colorless
- f. $N = 1.55$, $N_o = 1.54$

4. Cristobalite, SiO_2

- a. Pseudo-isometric (tetragonal?)
- b. 1696°C., 3085°F.
- c. 6-7
- d. Medium to dark grey

- e. Colorless
- f. $N_o = 1.487$, $N_e = 1.484$
- h. Usually associated with glass.

*Translucent Anisotropic Minerals with Strong Birefringence*1. Fayalite, $2\text{FeO} \cdot \text{SiO}_2$

- a. Orthorhombic
- b. 1205°C., 2201°F.
- c. 6.5
- d. Medium to dark grey

- e. Colorless, light green, yellowish green, yellowish brown.
- f. $N_g = 1.886$, $N_m = 1.887$, $N_p = 1.835$
- h. Frequently contains $2\text{MnO} \cdot \text{SiO}_2$ in solid solution.

2. Ferric oxide, hematite, Fe_2O_3

- a. Hexagonal
- c. 5
- d. Medium to light grey

- f. $N_o = 3.22$, $N_e = 2.94$ (Na)
- g. Frequently occurs as outer layer of scale.

3. Chromic oxide, Cr_2O_3

- a. Hexagonal
- b. 1900°C., 3452°F.
- d. Medium to light grey
- e. Green, depending on the thickness

- f. $N = 2.5 \pm$
- g. In stainless steels and other high chromium materials
- h. Not malleable at S R T. These inclusions are harder than chromite.

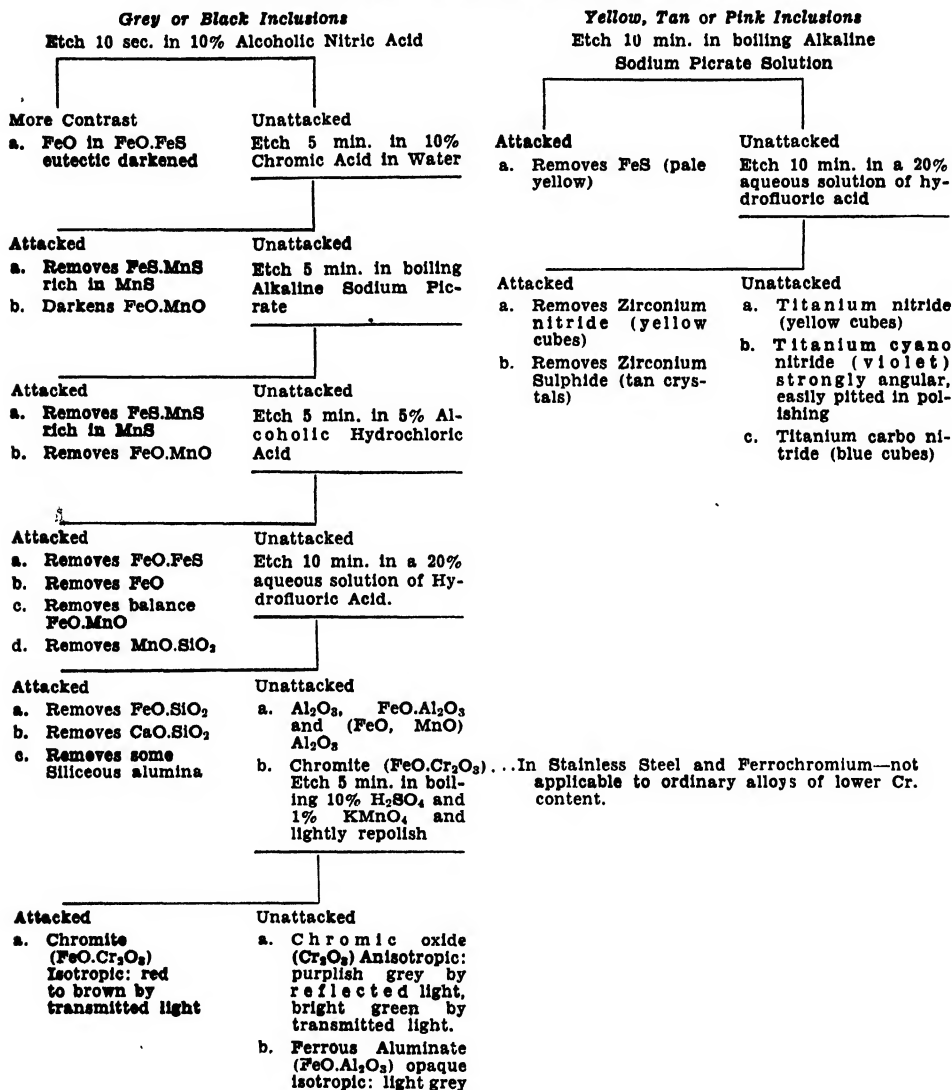
4. Aluminum Nitride, AlN

- a. Hexagonal
 - b. 2150-2200°C., 3902-393°F.
 - d. Dark to very dark grey
 - f. Birefringence (not available).
- Often show brilliant polarization colors.

- g. In chromium produced by the aluminic thermic process and in chromium steels containing aluminum.
- h. Frequently occurs as euhedral crystals.

Scheme for Etching Identification Tests

Appearance with Reflected White Light—X200, X500, X1000



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McQuaid-Ehn Test

By H. W. McQuaid*

Purpose of Test—The McQuaid-Ehn Test was developed in 1922 as a result of an extensive investigation into the effect of melting furnace practice on the hardenability of plain carbon case hardening steels. It was found that by carburizing at 1700°F. in a solid carburizer which would develop a definite hypereutectoid zone, and then permitting the material to cool slowly enough to develop a pearlitic struc-

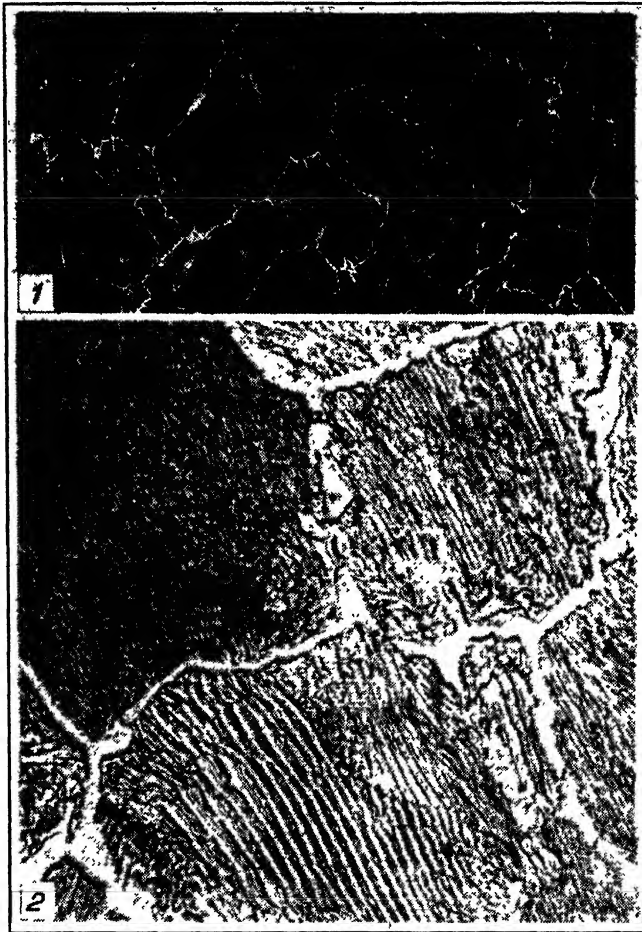


Fig. 1—Case structure of normal steel after McQuaid-Ehn test. White cementite network around dark pearlitic grains. $\times 100$.

Fig. 2—Same as Fig. 1 at $\times 1000$.

ture with free cementite in the hypereutectoid zone, there would be a definite structure developed depending upon the practice used in the melting furnace. By this means it became possible to predict from the carburized test the reaction of the final carburized product in quenching.

Since this test was first introduced it has been extended to cover not only plain

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carbon carburizing steels, but also alloy steels in all the commercial grades and the plain carbon steels including the tool steel ranges.

The importance of having methods of connecting properties inherent in a given heat of steel with the results to be expected in heat treatment and in the finished product, has resulted in many investigations into the characteristics developed by the McQuaid-Ehn Test. Other methods for the same purpose are given on page 754.

Pearlitic Structure Required—In order to properly make the McQuaid-Ehn Test, it is necessary to develop a pearlitic structure within the grain of the hyper-



Fig. 3—Case structure of abnormal steel after McQuaid-Ehn test. White cementite network with free ferrite (white) around dark lamellar pearlitic grains. $\times 100$.

Fig. 4—Same as Fig. 3 at $\times 1000$.

eutectoid zone after case carburizing. This requires the use of a carburizing compound which will develop a sufficient excess of cementite to permit, after the formation of the pearlitic structure within the grain, a clear indication of the disposition of the cementite itself. The work to be tested should, therefore, be carburized in a solid carburizer containing sufficient energizer to give a carbon content in the case well above the eutectoid range. There are many commercial carburizing compounds on the market which can be used for this purpose and as a

rule the standard carburizing compound used in the average plant will be found satisfactory.

Carburizing Temperature and Time—The work should be carburized at a temperature which is as close to 1700°F. as is commercially possible. However, very little difference will be found with a variation in temperature of from 1675-1725°F.

The time at temperature is determined by the depth of case obtained, and for most purposes it is only necessary to hold at temperature long enough to develop a sufficient hypereutectoid zone to be readily studied at 100× magnification. It is

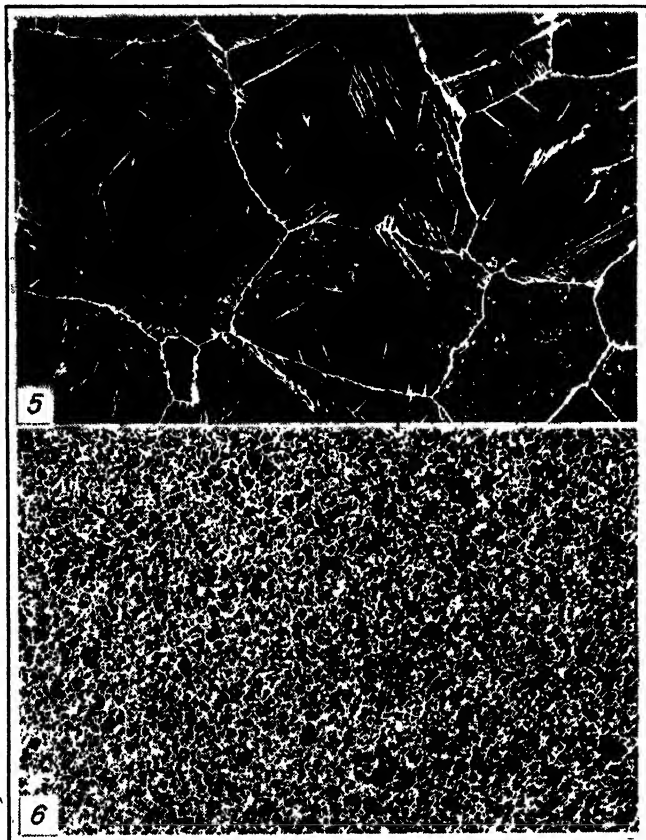


Fig. 5—Case structure of coarse grains after McQuaid-Ehn test. $\times 100$.

Fig. 6—Case structure of fine grains after McQuaid-Ehn test. Same composition as Fig. 5. $\times 100$.

better for most purposes to carburize until a case of approximately 0.050 in. is obtained, which will provide ample hypereutectoid zone for satisfactory study.

Cooling from Carburizing Temperature—The cooling time is governed to a large extent by the alloy content. In order to develop a satisfactory *pearlitic* structure in the hypereutectoid zone, the cooling rate must be very slow in the case of high alloy air hardening steels and can be relatively fast with the low carbon, low manganese steels containing no alloy. The cooling rate can be determined only by experience and depends not only on the alloy content but also on such factors as the size of carburizing container, size of specimen, and heating furnace. With plain carbon steels, the carburizing can be done in a commercial furnace and air cooled in the standard carburizing container. With the air hardening steels, such as the high nickel and chromium-nickel-molybdenum series, it is necessary to cool in the furnace. Where the carburizing is done in a laboratory furnace, it is quite common

to cool all tests in the furnace and with high alloy steels it has been found necessary to cool in the furnace at a very definite maximum rate.

The following minimum cooling rates through the critical range may be found satisfactory: 4 hr. for S.A.E. 2315 and 4615; 8 hr. for S.A.E. 2512; 16 hr. for Krupp steel (Ni 4%, Cr 1.5%); and 3 hr. for the other steels such as the plain carbon. 3115 and 6115.

Interpretation of Results—The interpretation of the test depends upon the examination of the pearlite and cementite in the hypereutectoid zone. In a strictly normal steel the structure within the grain boundaries is completely pearlitic, and if the grain is coarse the cementite exists as well defined lines of fine but continuous formation at the crystal boundary, as shown in Figs. 1 and 2. In a strictly abnormal steel the pearlite, if it is present at all as such, will be found to be very coarsely and irregularly lamellar and to have broken down completely at the grain boundaries to form massive cementite and free ferrite (Figs. 3 and 4). Here the cementite will be distinguished as ridges having a white background of ferrite. Between these two extremes will be found many types in which the pearlite becomes more coarsely lamellar as the steels become more abnormal, and there is an increasing amount of free ferrite surrounding the cementite at the grain boundaries. It will also be noted that there is a tendency for the cementite to become thicker and in some cases to become a discontinuous series of elongated particles.

Consideration of Grain Size—It was noticed at the time that this test was first developed that there was a variation in the size of the grain in the hypereutectoid zone from one heat to another and that this variation in grain size also served as an indication of the characteristics of the finished heat treated piece not only as far as hardenability is concerned but also in regard to the distortion and physical properties as well.

As usually made, particularly in the plain carbon steel, coarse grained steel will be quite normal with an increasing tendency toward abnormality as the grain size decreases. The coarse grained normal steels respond better to quenching, harden more deeply, and tend to distort considerably more than the finer grained more abnormal steels. The coarse grained normal steels have usually much lower resistance to impact and for this reason the finer grained steels are preferred for applications where resistance to shock loading is necessary. Because of the fact that the fine grained steels exhibit a much reduced tendency toward grain growth, they are usually preferred especially in the alloy grades for quenching directly from the carburizing temperature. In the plain carbon grades the difficulty met with in hardening because of soft spots is greatly increased with the fine grained, more abnormal steels, so that it is often necessary to quench these steels in a caustic or similar solution after carburizing.

The coarser grained steels respond more readily to the usual normalizing temperature to form a coarsely lamellar pearlite and hence are preferred in some plants because of the improved finish obtained in machining. By using a higher normalizing temperature, approximately 1800°F., to overcome the inherent resistance to grain growth in the finer grained steels, it is possible to improve the machinability of the fine grained steels to equal that of the coarse grained steels.

There is at present some difference in opinion as to the relative effects of normality and grain size. It is quite evident that the normality and the grain size are two independent characteristics and that steel can be made if desired which is fine grained normal or coarse grained abnormal. This is entirely a matter of furnace practice, but under present conditions most of the fine grained steels are slightly abnormal and the coarse grained steels are normal, and the desired characteristics can be commercially obtained by proper selection according to grain size. For this purpose there are available grain size charts which permit of classification according to grain size as revealed by the McQuaid-Ehn Test.

Austenitic Grain Size in Steel

By E. C. Bain* and J. R. Vilella†

PART I. SIGNIFICANCE OF GRAIN SIZE

Introduction—Probably no subject relating to the heat treatment of steel has received more attention in the last few years than that of austenitic grain size. This interest came about as a response to the need for a rational understanding of those more subtle, but important, factors of steel quality which cannot be explained by the composition of the steel as ordinarily reported in the usual analysis. In brief, the explanation was found to lie largely in the grain size of the austenite, established during the final heating above the critical range. The *extra analytical* properties finally secured depend in large part upon the actual grain size of the austenite which transforms to set up the microscopic structure existing in the heat treated steels as tested and used. Once the trends of austenitic grain growth in steel were understood it was apparent that a clear cut, positive correlation existed between properties or behavior and the true mean grain size established in the final heating. This close relationship seemingly does not exist between the securable properties and any *quasi* grain size which might have been established at some other temperature, or with some treatment, not used in the practical final heat treatment which is responsible for the properties. This reasonable circumstance was seemingly overlooked for a time, owing perhaps to a lack of confidence in means of quickly ascertaining the austenite grain size of any specimen of steel about to be quenched in any suitable manner. Yet this is the grain size which would be expected to have a direct, rather than fortuitous, significance. Throughout this article *grain size* will always mean the true austenitic grain size established at elevated temperature in an indicated significant heating.

The pioneer contributions to this advance in the technology of heat treated steels, both in manufacture and in use, came from several sources. In Sweden the study¹ progressed as an inquiry into the characteristic attributes, particularly of acid open hearth tool steel. Another approach² was that which related to the hardenability of comparatively low alloy, low carbon, carburizing steels quenched directly from the carburizing box. A more advanced development³ of this subject, on the part of manufacturer and user, was that of fine carbon tool steels of controlled hardenability (and toughness) accomplished without significant changes in analysis, and the subsequent extension of these achievements into the steels of greater tonnage. All these studies converge in the building up of a simple concept of grain size effects and it is toward the setting forth of this simplification as applied to medium and high carbon and low alloy heat treated steels, that this article is directed.

The Usefulness of the Older Observations—It was not unknown in old art that a coarse fracture of a hardened and broken piece of steel accompanies excessive brittleness, and that equally hardened steel which requires greater effort in breaking exhibits a finer, "silky" fracture. The many individual facets of the broken surface are large in the first case and small in the second. To what the size of the individual facets refers, and upon just what this corresponding coarseness or fineness depends, was, however, not obvious, and has only more recently been known. Another observation was probably made long ago; similar steels, in sections too large to be hardened throughout, hardened more deeply, in a certain medium, whenever the fracture appearance was coarse, and less deeply when the fracture was fine. Some twenty years ago, more or less, certain manufacturers were introducing an alloying element to preserve the fine fracture and its attendant toughness, and adding extra manganese to restore the deeper hardening characteristics. When a single bar or heat of steel was under consideration it was observed long ago that high heating temperatures, as in the Metcalf test, induced the deeper hardening and the attendant coarser fracture but any cause and effect relationship between coarseness and depth of hardness penetration in the quenched piece was not specifically mentioned until more recently. Indeed it was erroneously supposed by some that the quenching rate in any medium was universally accelerated if the steel was quenched from a higher temperature. This is now known

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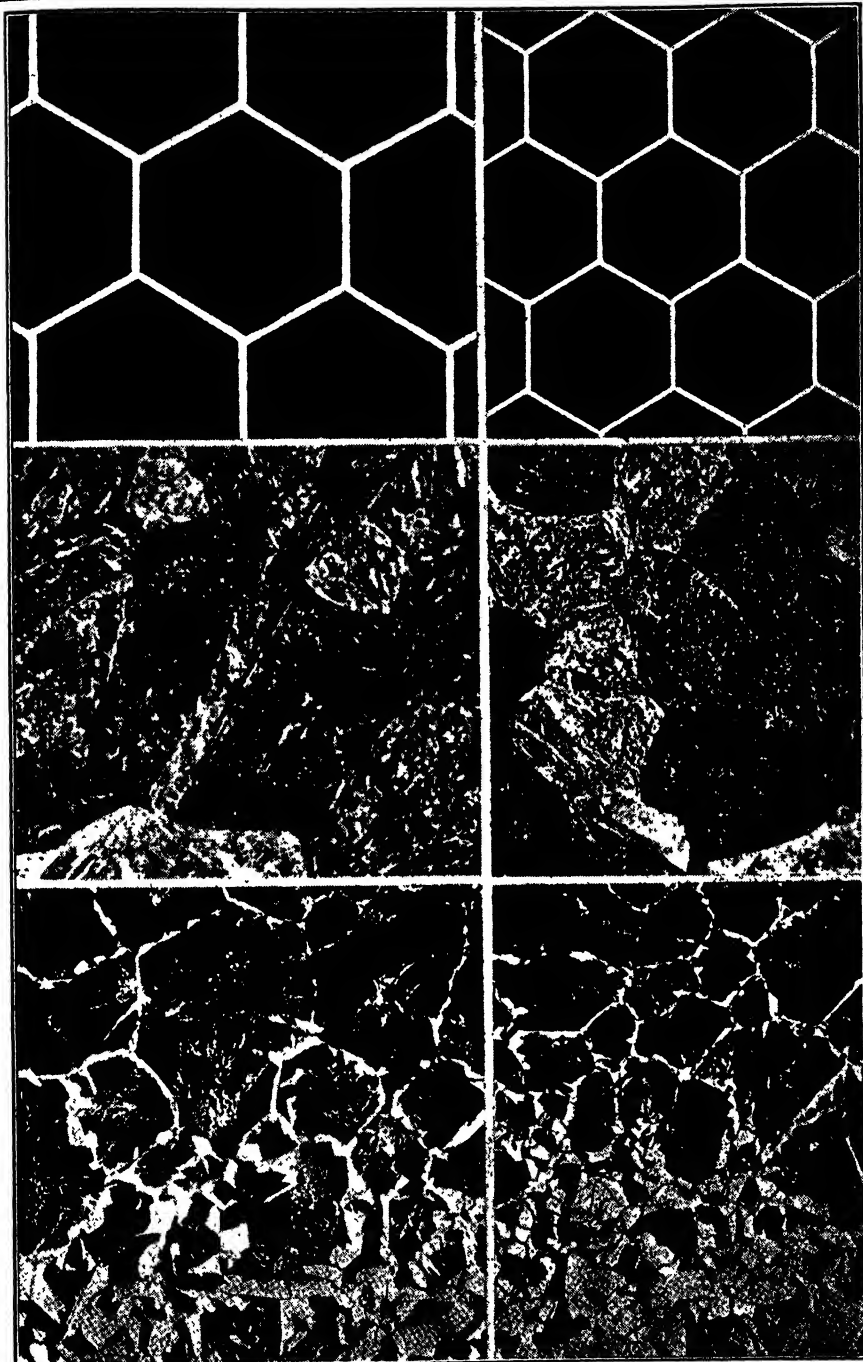


Fig. 1

Fig. 2

Fig. 1—Upper, idealized hexagonal network for mean grain size 1, A.S.T.M. scale. Center, austenitic grain size 1, i. e., up to $1\frac{1}{2}$ grains per sq. in. of image at 100X as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. Lower, from A.S.T.M. Specification E19-33, hypoeutectoid structure in carburized steel (8 hrs. at 1700°F.) with grains up to $1\frac{1}{2}$ per sq. in. at 100X.

Fig. 2—Upper, same as Fig. 1, but for mean grain size 2. Center and lower, same as Fig. 1, but for $1\frac{1}{2}$ -3 grains per sq.in.

to be untrue⁴ in any general sense. Since steels of almost identical composition (insofar as the ordinary elements reported in an analysis are concerned) are available, each of which will develop its own particular grain size at a certain temperature, grain size variation may be studied quite independently of the heating temperature, which may thus be the same for all. When the interest centers in the same identical steel then heating temperature or heating schedule is varied to produce the grain size contrast. By employing both methods of grain size control the broad effects have become familiar.⁵ In a general way the effects of the previously existing austenite grain size may be summed up in Table I.

Table I
Effects of Previously Existing Austenite Grain Size

Property	Trends in Heat Treated Steel Products	
	From Coarse Grained Austenite (No. 5 and Above)	From Fine Grained Austenite (Finer than No. 5, 5-8)
Hardenability	Deeper hardening.....	Shallower hardening.....
Toughness at same hardness.....	Less tough.....	Tougher.....
Distortion	More distortion.....	Less distortion.....
Quenching cracks.....	More prevalent.....	Usually absent.....
Grinding cracks.....	More susceptible.....	Less susceptible.....
Internal stress.....	Higher.....	Lower.....
Retained austenite.....	More.....	Less.....
<i>For Annealed and Normalized Products</i>		
Machinability	(Rough) better.....	(Rough) inferior.....
Machinability (special cases).....	(Fine finish) inferior.....	(Fine finish) better.....
Formability (special cases).....	Superior.....	Inferior.....

Before considering the yard stick for grain size evaluation and the technique by which it is easily accomplished, it is desirable to consider the habits of austenite as it forms upon heating and establishes the grains which later grow in characteristic ways (and become of such importance).

The Formation and Growth of Austenite Grains—When a piece of carbon or low alloy steel is heated above the so-called critical point the ferrite and carbide react with one another to form austenite. The austenite is a crystalline phase differing distinctly from either the carbide or ferrite of which the steels under consideration are inevitably composed. Like any metal composed of a solid solution, it exists in the form of polyhedral grains. This reaction begins at a number of points, of necessity, in the interface of the carbide (particles or plates) and the ferrite. In each such growing particle of newly formed austenite, carbon and iron and other elements from the carbide particles are dissolved as well as iron and other elements also from the ferrite. Each little island of austenite grows until finally it reaches to its similarly growing neighbors.⁶ In the ideally simplified case there would be just as many grains of austenite as there were separate original nuclei, and in a fairly coarsely spheroidized steel this is nearly realized. In the general case, some of the islands of austenite must, of course, grow more vigorously than others and, therefore, when a large grain encounters a small one the small one is forced to shift its orientation layer by layer, and thereby, as it loses its identity, it is absorbed into the larger grain. Probably this happens frequently in certain steels and rarely in others. Now if the steel is far from eutectoid in composition and is heated below the A_{c1} or A_{cm} temperature, some islands of ferrite or cementite will remain unabsorbed regardless of period of heating. These undissolved proeutectoid constituents appear to block grain growth so that this initial set of austenite grains are preserved even after long heating. When the temperature of heating is above A_{c1} or A_{cm} , any ferrite usually disappears quickly enough, but the carbide, although ultimately soluble, dissolves rather slowly so that, depending upon its coarseness, more or less of the carbide persists even after surprisingly long time intervals. It is important here to note that the first grain size of the austenite depends largely upon the number of nuclei and that so long as any moderate amount of carbide remains these grains do not greatly change.

In pearlitic steels the effective nuclei are often located in the interior of a region of lamellae, while in spheroidized steel each spheroid of carbide is a poten-

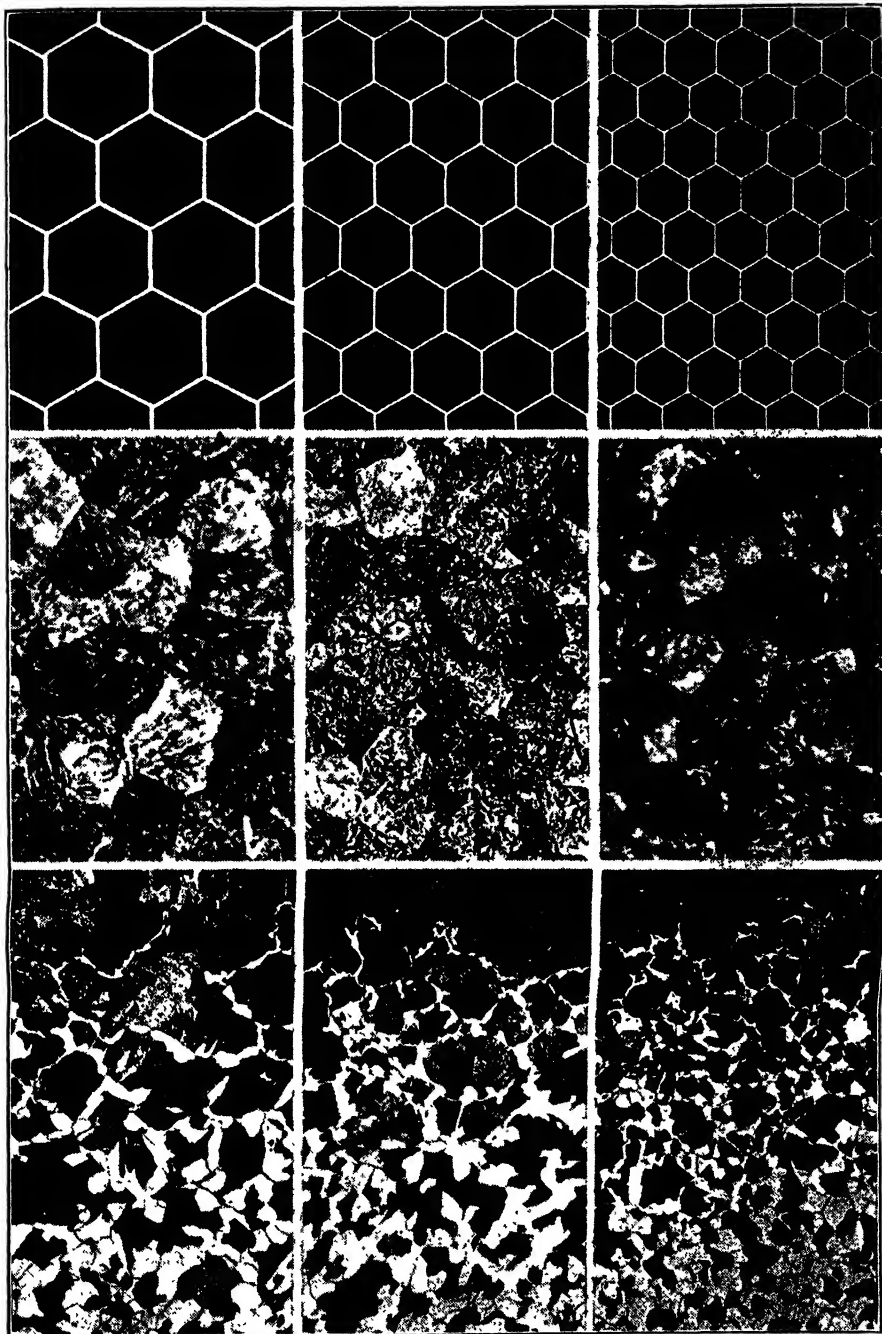


Fig. 3

Fig. 4

Fig. 5

Fig. 3—Upper, idealized hexagonal network for mean grain size 3, A.S.T.M. scale. Center, austenitic grain size 3, i. e., 3-6 grains per sq. in. of image at 100X as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. Lower, from A.S.T.M. Specification E19-33, hypoeutectoid structure in carburized steel (8 hrs. at 1700°F.) with 3-6 grains per sq. in. at 100X.

Fig. 4—Upper, same as Fig. 3, but for mean grain size 4. Center and lower, same as Fig. 3, but for 6-12 grains per sq.in.

Fig. 5—Upper, same as Fig. 3 and 4, but for mean grain size 5. Center and lower, same as Fig. 3 and 4, but for 12-24 grains per sq.in.

tial nucleus. When the spheroidization is fine many such nuclei are ineffective because of the mechanism mentioned above. However, at ordinary quenching temperatures the original austenite grain size pattern is largely retained and this is termed the "uncoarsened grain size" to which almost all practical heat treating of carbon steel relates. The number of nuclei seemingly depends upon:

1. Previous mechanical and heat treatment, as it affects:
 - a. Distribution of carbide, lamellar or spheroidal, i. e., the structure.
 - b. Fineness of carbide dispersion.
 - c. Homogeneity of steel.
 - d. State of stress or deformation.
2. Composition of ferrite and carbide.
3. Nonmetallic inclusions:
 - a. Submicroscopic.
 - b. Microscopic.

Subsequent changes in the grain size of the austenite occur with heating as it reaches toward and beyond the normalizing range of temperature. Many steels not so made as to restrict grain growth begin to undergo mild coarsening about as soon as the major part of the carbide (or ferrite) is dissolved. With rising temperature, such steels appear to coarsen rather regularly without any abrupt changes, presumably by the successive coalescence, here and there, of two or sometimes three grains to form one new grain. At any rate there is at no point any marked disparity of grain size. When a special, less soluble, carbide exists, as for example in vanadium steels, the carbide particles persist to astonishingly high temperatures such as 1750-1800°F., and little grain growth occurs so long as many such vanadium-rich carbide particles remain.

In similar manner certain nonmetallic substances appear to accomplish this same inhibition to grain growth. This broad effect of inert particles has long been known in the manufacture of tungsten filament wire, in which case the extremely inert and refractory oxide of thorium present as visible particles, at least in part, acts as the grain growth inhibitor.

An interesting effect of these so-called grain growth inhibitors is that when they finally become ineffective at some elevated temperature, either as a result of solution or coalescence, or by mere inefficacy or insufficiency, the degree of grain growth is likely to be greater than in a steel free from such restraint. Such steels retain a fine grain almost unchanged during heating at successively higher temperatures until abruptly, here and there, a single large grain forms out of as many as 100 or more former small grains. Prolonged heating, or a rise in temperature, will generally convert the remaining fine grains to the same type of large grain as first formed upon reaching the coarsening temperature. Inhomogeneities of the steel tend to broaden the temperature range of two distinct grain sizes. This state of affairs in the marked grain growth range is sometimes spoken of as "duplexing". It has no special significance, merely marking a natural transition stage from fine to coarse grains, when the change is large and fairly abrupt and unfinished.

It should be borne in mind that the persistence of carbide and attendant retention of small grains is often a matter not of equilibrium but of rate of solution and carbide frequently remains undissolved for 30 min. or more in eutectoid or even hypoeutectoid steel heated well into the pure austenite (equilibrium) temperature range.

PART II. DETERMINATION OF AUSTENITIC GRAIN SIZE

Introduction—In Part I, the grain size established in austenite at various temperatures has been discussed in a qualitative or comparative way. It now becomes necessary to go into greater detail and to choose some quantitative basis of grain size estimation. Now, grains are solid bodies, and to be meticulously correct one should speak of an average grain size in terms of volume, such as fractions of a cubic inch or a cubic millimeter; or one could better use the reciprocal, so many grains per cubic inch or cubic millimeter. Actually, this is unnecessary and probably confusing. Grain size estimation or grain counting is finally accomplished by viewing a polished *plane* section under the microscope and the boundaries of the grains as viewed lay out a network on a *plane* surface. Now the number of grains per unit area so sectioned upon a plane, or the average area of these

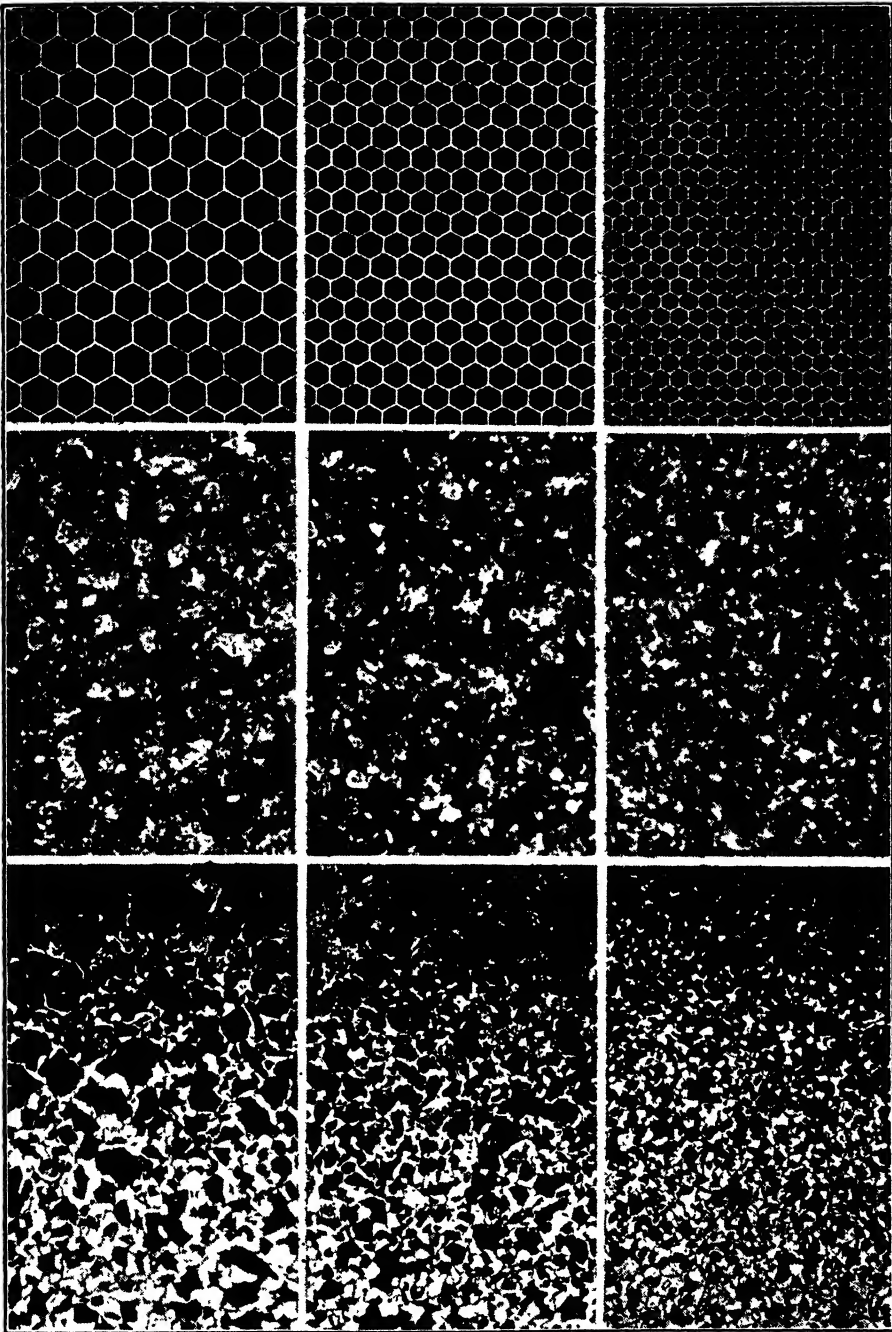


Fig. 6

Fig. 7

Fig. 8

Fig. 6—Upper, idealized hexagonal network for mean grain size 6, A.S.T.M. scale. Center, austenitic grain size 6, i. e., 24-48 grains per sq. in. of image at 100X as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. Lower, from A.S.T.M. Specification E19-33, hypoeutectoid structure in carburized steel (8 hrs. at 1700°F.) with 24-48 grains per sq. in. at 100X.

Fig. 7—Upper, same as Fig. 6, but for mean grain size 7. Center and lower, same as Fig. 6, but for 48-96 grains per sq.in.

Fig. 8—Upper, same as Fig. 6 and 7, but for mean grain size 8. Center and lower, same as Fig. 6 and 7, but for 96 grains and more per sq.in.

rough polygons serves quite as well as a measure of grain size as would a figure based on three dimensions or volume. If one cares to do so he can always think of the grains as solid bodies while reporting in terms of their mean sections on a representative plane. The actual units employed in such grain size estimates are not uniform for different metals in different countries. The common terms for reporting grain size are:

1. Grains per sq.mm.
2. Average area of grain in sq.mm.
3. Mean diameter of grain (in mm.).
4. Arbitrary numbers (exponential), Timken, A.S.T.M., index based upon the formula.

$$\text{Number of grains per sq.in. at } 100X = 2^{N-1}, \text{ in which the grain size index} = N.$$

The designation mean diameter (3) is fortunately not much used since it is not easily estimated directly and as a derived number is ambiguous and less useful than the direct observation. Any scheme showing number of grains per unit area (either of specimen or microscopic image at known magnification) is vastly preferable.

Practically all austenitic grain size studies and specifications in America refer to the Timken, A.S.T.M. index numbers. For convenience they are tabulated with corresponding dimensions in Table II, and extended somewhat beyond the usual range employed. In Table II, the last column headed "Grain Boundary Area, mm.² per mm.²," shows the minimum possible interface area. The effective intergranular surface will be greater, particularly in the finer grain sizes, due to the undissolved carbide particle surfaces and to irregularities in the true austenite grain boundaries.

It is often desirable to match the microscopic image discussed below with the standard network charts, such as are included herewith (Fig. 1-8), using a magnification either lower or higher than 100X, respectively, for coarse or fine grains. The following rules apply:

- For 50X, report 2 numbers lower than matching chart.
 For 200X, report 2 numbers higher than matching chart.
 For 400X, report 4 numbers higher than matching chart.
 For 800X, report 6 numbers higher than matching chart.

Idealized grain boundaries in a hypothetical hexagonal network are shown in Fig. 1-8 for the corresponding A.S.T.M. grain sizes as tabulated in Table II. These are probably the best comparison standards for general grain size estimation.

Table II
Comparison of Systems for Reporting Grain Size

Timken, A.S.T.M. No.	Grains per sq.in. of Image at 100X			Grains per mm. ²	Mean Area per grain, mm. ²	Grains per mm. ² Approx.	Grain Boundary Area, mm. ² per mm. ²
	Max.	Min.	Mean				
-3	0.09	0.05	0.06	1	1	0.7	2.4
-2	0.19	0.09	0.12	2	0.5	2	3.3
-1	0.37	0.19	0.25	4	0.25	5.6	4.7
0	0.75	0.37	0.5	8	0.125	16	6.7
1	1.5	0.75	1	16	0.062	45	9.5
2	3	1.5	2	32	0.031	128	13.4
3	6	3	4	64	0.0156	380	19
4	12	6	8	128	0.0078	1020	27
5	24	12	16	256	0.0039	2900	38
6	48	24	32	512	0.00195	8200	54
7	96	48	64	1024	0.00098	23000	76
8	192	96	128	2048	0.00049	65000	107
9	384	192	256	4096	0.000244	185000	150
10	768	384	512	8200	0.000122	520000	215
11	1536	768	1024	16400	0.000061	1500000	300
12	3072	1536	2048	32800	0.000030	4200000	430

Some of the data of this table are from unpublished work of R. H. Aborn and J. J. B. Rutherford.

Preparation and Microscopic Examination of Specimens for Grain Size Rating—Thus far it has been assumed that the grains could be rendered clearly visible in a microscopic specimen and an estimate of their size arrived at either by counting over a known area of image at known magnification, or by comparing such images

on the microscope ground glass with charts having standard graded grain size patterns marked out. This is, in general, easily done, especially for grain sizes No. 6 or coarser. Occasionally it is more time consuming for finer grain sizes but never impossible. In principle, the problem of grain size determination in austenite is rendered more complex than that in brass, for example, because one must estimate the grain size of a constituent which is no longer present. If one had a means of examining under a microscope the heated steel ready to be quenched this complication would not arise, but such technique is not practical. Fortunately, how-

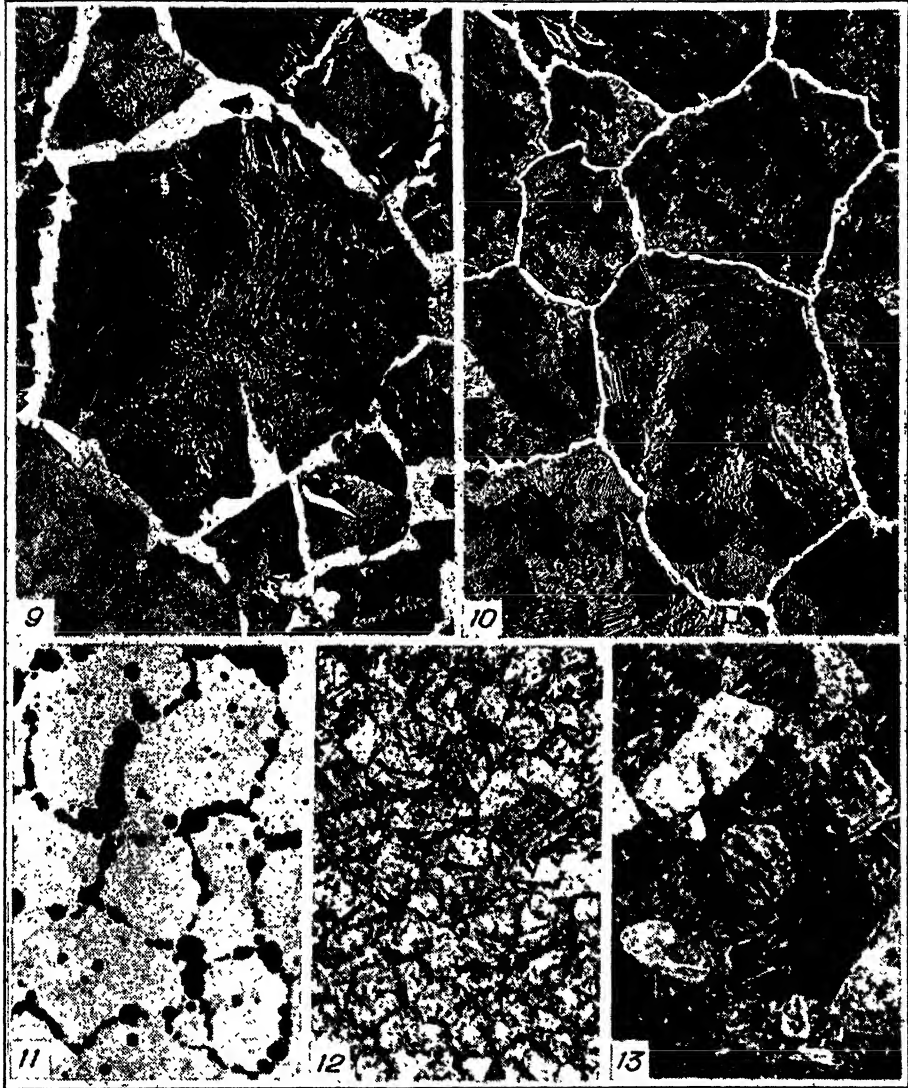


Fig. 9—Ferrite network properly developed for grain size estimation in hypoeutectoid steel, X300. Fig. 10—Carbide network properly developed for grain size estimation in hypereutectoid steel, X300. Fig. 11—Black etching network of fine pearlite properly developed for grain size estimation in incompletely hardened eutectoid steel, X125. Fig. 12—Grain size developed in fully hardened steel (martensite) for grain size estimation, X100. Fig. 13—Grain size developed in fully hardened and tempered steel (troostite or sorbite) for grain size estimation, X100.

ever, austenite transforms in such a way as to reveal its former grain boundaries unequivocally. This comes about through three circumstances:

1. Proeutectoid rejections in either hyper- or hypoeutectoid steels can generally be forced to the grain boundaries to form a complete, or nearly complete, network.
2. Transformation reactions even in eutectoid steel begin dominantly in the grain boundaries and may be interrupted when a network is developed.
3. Martensite has limits of orientation depending upon that of the parent austenite grain and hence can, with suitable agents, be etched much like a pure metal to develop contrast among grains.

In some respects the fact that the grain size of austenite is estimated upon its decomposition products and not upon the constituent itself is an advantage; for this circumstance permits outlining the grain boundaries with constituents which may have great visual contrast with the main portion of the grains. Even under the worst conditions the problem, however unique, is not more difficult than that for brass or other single constituent metals. As it happens, carbon or low alloy steels with a carbon content somewhat remote from the eutectoid, that is, distinctly hypoeutectoid or hypereutectoid, reject, upon slowly cooling through the transformation range, either ferrite or carbide, respectively; the rejection of these proeutectoid constituents occurs largely at the grain boundaries after which the remainder of the austenite transforms to a black etching pearlite. The transformation of eutectoid austenite, beginning characteristically in the grain boundaries, makes possible the formation of some fine pearlite (nodular troostite) in the grain boundaries after which the remainder of the austenite may be caused to transform to light etching martensite. Thus eutectoid steels, from which no separate boundary constituent may be rejected, may quite as easily have the grain boundaries clearly laid out. It is obviously of no consequence which is darker, the boundary or the interior body of the grain.

Now, any steel sample heated at any temperature, depending upon carbon content, above A_{c1} , A_{c2} , or A_{cm} is made up of austenite (in which carbide may be present or not), which is composed of grains and an interest may exist in the size of those grains; the foregoing paragraph shows how it is always possible to learn what this grain size may be. Often the steel may be normalized in handling and it will be the high temperature austenitic grain size in which interest centers. In that case one may either simulate the normalizing treatment in a small laboratory furnace and establish the grain size in question, or a piece may be carried along in the commercial furnace. In any event the grain size will have been established at the conclusion of the heating period and the only problem thereafter lies in so cooling the specimen as to make that grain size clearly readable under the microscope. More often the interest lies in the grain size in the steel as heated for the final quench (water, oil, or air) and in this case also either the laboratory furnace may be employed or a piece going through commercial treatment may be selected for grain size examination. In any case it is only the austenitic grain size actually established in the particular heat treatment under consideration which can infallibly correlate with the steel properties to be secured. The austenite grain size is not affected in any way by the kind of cooling applied and any representative specimen selected for examination from the heating furnace may be cooled wholly as desired on the basis solely of making its grain size apparent.

For example, if it should be desired to secure a steel which would not coarsen to an extent beyond a No. 5 grain size, and the customary heat treatment is nominally at 1475-1500°F., then one should cut a specimen of dimensions suited to the application and so heat it, either along with a commercial batch, or in a small furnace for the same period and then cool it, as indicated below, to give the best marking out of grain size. If the steel is normalized or homogenized prior to such heating for hardening then this treatment should preferably precede the heating for test. To take care of possible furnace irregularities some prefer to heat 50°F. or even 100°F. higher than the commercial schedule, on the assumption that if a steel does not coarsen at 1550°F. it certainly will not do so at 1475°F., which is generally true. Testing at much higher temperatures than employed in practice is not correct in grain size study because the test then departs too much from the conditions in which interest centers and valuable information is lost.

Another example might be cited in which a certain degree of coarsening is desired in the normalizing range. In this case the proper preferred normalizing

temperature should be used either in the commercial furnace or in a laboratory furnace for the customary period of time.

The essential point is, that for pertinent information as related to quenching and tempering and the final properties of heat treated steel the grain size should be established at the approximate quenching temperature. For useful information on grain size effects in other heating, such as normalizing (or forging), the higher temperatures employed therein should be used in the grain size determination also. It will be seen that failure to observe this consistent procedure may result in erroneous conclusions.

Having developed the grain size in the properly heated, and therefore austenitic, steel, the cooling is carried out in such a way as best to reveal this grain size. This will vary with the type and carbon content.

Hypoeutectoid Carbon Steels—In most cases with a carbon content between 0.25 and 0.60%, it will be sufficient merely to cool a specimen about $\frac{1}{2}$ in. in dia. in air. The ferrite will form chiefly in the grain boundaries and mark out the grains as in Fig. 9. When the grain size is small, complete envelopes (particularly of ferrite) will generally not form, but this offers no difficulty. One austenite grain still forms, in general, only one area of dark pearlite so that the eye readily recognizes the grains either for counting or for comparison.

When the composition is only slightly hypoeutectoid the steel may either be treated in accord with directions below for eutectoid steel, or may be cooled to about 1340°F. and held there 10 or 15 min. before final cooling. This cooling will generally form a very good network of ferrite.

Hypoeutectoid Alloy Steels—Omitting carburizing steels (discussed below) these steels should in general be cooled by the second method for hypoeutectoid carbon steels, allowing still more time at about 1340°F. Otherwise they may be treated as for eutectoid steels (below). An excellent improvement on this method is to hold at some temperature near 1300°F. for sufficient time to establish a ferrite network and then quench. Subsequent tempering to some 800°F. (a minute is sufficient) develops a black etching sorbite in the body of the grains. The most brilliant contrast develops upon etching. Higher alloy steels require the longer holding time. The optimum can be determined once for all by a series of specimens held for three or four different periods.

Hypereutectoid Steels—These steels are easily cooled to develop a fine carbide network, the best rate depending upon composition. Unless the carbon is above 1.10, they are best treated as eutectoid steels (below). Equally satisfactory results are secured by the method of holding at 1300-1340°F., quenching and reheating roughly at some 800°F. The hypereutectoid zone of a carburized steel is handled in the same way, as discussed below. Fig. 10 shows a carbide network marking out the grains.

Eutectoid Carbon Steel—A specimen of $\frac{1}{2}$ -1 in. dia. is properly heated in the range in question and quenched into water; one end may be kept out of the water. The center, or the unquenched end, will be uniform fine pearlite, in which grain size is not discernible; the outer zones will be martensitic. Between the two will be a zone in which the martensitic body of the grains will etch lightly, while the many nodules of fine pearlite in the grain boundaries will etch black and mark out the grains. When this method becomes somewhat ambiguous in the finest grain sizes, and it is still desired to have an accuracy of one grain size number, the estimation should be made in the fully hardened zone as for hardened steel. Fig. 11 shows grain size marked out by black etching fine pearlite in the boundaries in the transition zone.

Fully Hardened Steel—It may happen that it is desirable to know the grain size established in heating a steel which has however already been quenched, and even perhaps tempered, the latter being the most difficult case. This can also be accomplished by suitable etching of the wholly martensitic structure. Two or more slight repolishings and etches may be necessary. The etching agent (Vilella's Martensite Reagent) which develops contrast between the martensite of individual austenite grains is made up as follows: Dissolve in 95 cc. of ethyl alcohol 1 g. of picric acid and 5 cc. of concentrated hydrochloric acid.

The prior true austenitic grain size may be determined in hardened steel which has been definitely tempered and moderately softened. Indeed, there is an optimum

degree of tempering which provides the greatest contrast among the grains. Fig. 12 shows the structure of hardened steel etched for grain size estimation, and Fig. 13 shows a hardened and tempered steel.

Carburizing Steels—In cases wherein the steel under consideration is to be case carburized and quenched directly from the carburizing box, the important grain size is that established under those precise conditions when the steel is removed from the carburizer; the grain growth characteristics of the steel are often greatly altered by the infusion of carbon, and an examination of the original low carbon steel heated to the carburizing temperature would be misleading (that is, the core of carburized pieces). Accordingly the specimen should be properly cooled so as to develop a carbide network in the high carbon zone when removed at the conclusion of carburization; in brief, handled thereafter exactly as for any hypereutectoid steel. When, however, the carburized steel is to be reheated, the carburized grain is not significant and the specimen should be reheated in accord with practice before cooling to mark out the grains.

Grain size estimation was early carried out upon carburizing steels and the observations upon the hypereutectoid zone were interesting. In the first place, grain size estimation on the microscope is, perhaps, easiest upon hypereutectoid compositions due to the extra contrast of the usually clear carbide envelopes or network. Certain other features* of the carburized structure are, metallographi-

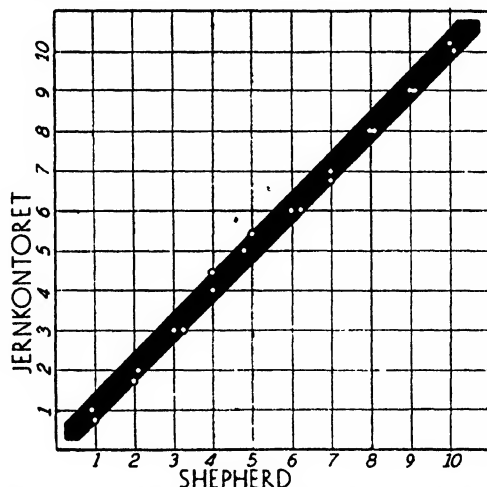


Fig. 14—A comparison of the Jernkontoret and Shepherd fracture standards 1-10, each in terms of the other. Note similarity.

cally, fascinating, and the examination of carburized specimens of various steels not commercially carburized has been frequently carried out as a standard test. For details of this procedure the reader is referred to page 750. The only point to be remembered is that steels indistinguishable in properties and grain size as properly heat treated may possess vast differences in grain size as carburized.

Section-Size Distribution—Inevitably some grains of the mean size, or larger, will be sectioned in such a way as to show a small polygonal surface in the image. Hence an occasional small polygon should not be reported as indicating mixed structure. When, however, a cluster of small grains is found they should be taken into consideration, for it is not possible to section more than about three adjacent large grains to yield small plane grain sections. Generally speaking, in the case

*A most interesting structural feature of carburized steels becomes apparent when they are cooled exactly alike. It has to do with the regularity of the pearlite and the extent to which it fills the envelopes of the grains marked out by proeutectoid carbide and is designated "Normality" or "Abnormality". It is sufficient to note here that this feature is controlled by composition and grain size in the carburized state of steels amenable to the classification. With constant composition, fine grains infallibly favor abnormality, coarse grains favor normality. With constant grain size the normality is then a measure of effective content of deep hardening elements in solution, these elements favoring normality.

of a uniform grain size, about three-fourths of the field will show "grains" within one grain size bracket. Most of the remaining quarter of the field will be made up of the next smaller size with a few still smaller polygons.

Austenitic Grain Size from Fracture—In the introduction mention was made that a correlation of the properties of hardened steel had early been made with the coarseness or fineness of the fracture surface of a break on the hardened steel. As early as 1926 this relationship was used as a quantitative measure of certain aspects of steel quality at the Uddeholm Steel Works in Sweden. At first only five recognized grades of fracture were employed, but later the work was extended through the supervision of Jernkontoret, and in 1927 a 10-step scale was recommended as a suitable measure of tool steel quality; sets of standard fractures in 22 mm. square bars were made up under the direction of Dr. Ragnar Arpl. These bars covered the full range of coarseness and fineness, usually encountered, by steps which to the eye appeared evenly spaced.

In America also, B. F. Shepherd employed an examination of hardenability and fracture appearance as a measure of the probable suitability of steels for certain purposes. Shepherd prepared a set of graded standard fractures in which the entire cross section of the standard bars was hardened. To gain an adequate

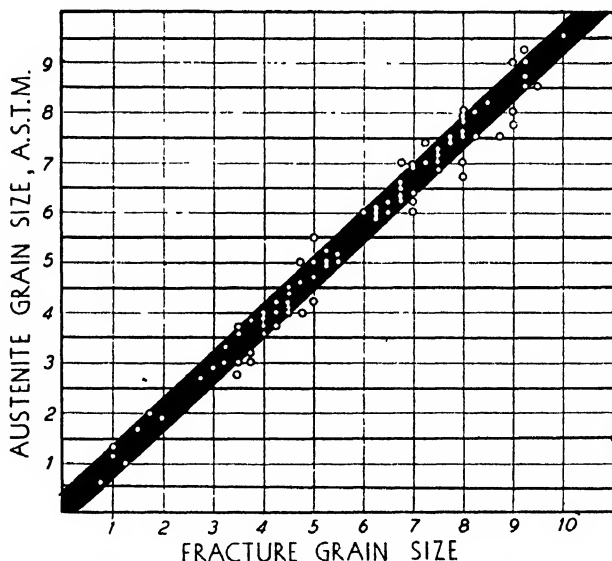


Fig. 15—Relation between fracture rating and the true prior austenitic grain size in hardened and broken specimens.

impression of different bars of steel he generally hardened the specimens (of definite section) from four heating temperatures, 1450°, 1500°, 1550°, and 1600°F., and secured thereby a pattern for the coarsening of the steel at increasing temperatures. The fracture was compared with the series of standards similar indeed to the Swedish standards. The latest standard fractures (hardened throughout in both cases) of Shepherd and Jernkontoret, numbered serially 1-10, each as compared with the other, are shown in Fig. 14. For most practical purposes they may be regarded as the same.

It will have become almost obvious by this time that there is a marked degree of parallelism, more than purely fortuitous, between coarseness of fracture and the austenitic grain size which existed in the fracture specimen before it was quenched and broken. This relationship proves to be closer than was at first supposed. The estimation of a great many fractures shows that the relationship between the Shepherd or Jernkontoret fracture numbers and the austenitic grain size responsible for the fracture appearance is about as shown in Fig. 15. It should be borne in

mind that the eye is able to arrive at a mean value of the coarseness of a fracture and that for correlating fracture number with austenitic grain size the mean value of the latter should be used. Thus if a specimen were accurately rated 65% No. 6 and 35% No. 4, then its mean grain size would be about 5.3 and it would exhibit a fracture about midway between 5 and 6. There is one interesting fact about estimating prior austenite grain size by fracture. The eye is more *sensitive* to slight changes in fracture appearance than is the corresponding mean grain size estimation on the microscope. Experienced observers of fractures will agree within one-half, and often within one-quarter, of a single step in the fracture series. There is probably no urgent need even for as many steps as exist in either the A.S.T.M. grain size rating or the fracture rating. The properties which are reflected by grain size are not sufficiently modified by small changes to warrant great accuracy in reporting grain size either by fracture or by microscopic examination.

A word should be said about the fracture appearance from mixed grain sizes. Actually there will be large facets mixed with the fine on the fracture surface but the eye does not once recognize this unless the fracture is fairly coarse; instead, undue influence is exerted by the few coarse facets. Nevertheless an experienced observer can pick out "duplexed" specimens reliably from fracture appearance once he acquaints himself with a few known specimens of mixed grain size. (The mixed grains must really have existed at the time of quenching, and not have been found only after some other unrelated heating.) A few rare anomalous cases are found in which considerable experience is necessary to estimate actual grain size from fracture. The most notable of these is the case of an austenite grain which at elevated temperature coarsens abnormally, having been inhibited until high temperature is reached. The surface of each grain is slightly matte, not brilliant, suggesting a fine grain size, while the large grain size is also apparent from a faint appearance of large facets. The explanation⁵ for this condition has been suggested and occurs too rarely to be serious.

It is easy and practical to combine a hardenability test with the grain size evaluation by fracture as has been done by Shepherd. A standard specimen size must then be adopted and rigidly maintained and the fracture grain size estimated upon the fully hardened or martensitic rim. The depth of this rim can be measured (by 64ths of an in. in Shepherd's technique) after it is rendered visible by etching. Shepherd reports eight numbers which largely classify certain grades of carbon steel as to their suitability for hardened parts. The first four numbers are depths of hardened zone in 64ths of an in. as quenched from 1450°, 1500°, 1550°, and 1600°F., respectively, while the second four numbers are the fracture numbers (Shepherd or Jernkontoret scale) of the hardened zone of the same specimens. It should be stressed that the information secured by this P-F (P = penetration of hardened structure; F = fracture rating) test goes far toward giving a full account of the nature of carbon steel. Obviously alloy steels may harden throughout such large sections that the hardenability feature is inapplicable; the fracture grain estimation is still valid, however.

The most rapid examination of a steel for significant grain size characteristics consists of first rating the fracture*; if it is not indicative of mixed grain size the A.S.T.M. grain size may be reported at once, or if the fracture shows the probability of such a condition it may be polished, etched, and rated microscopically by the charts of Fig. 1-8, inclusive.

Summary—The grain size established in the austenite of a bar of steel ready to be cooled or quenched plays an important part in determining the properties secured. This grain size is generally fine at ordinary quenching temperatures but coarser at higher temperatures, namely, normalizing temperature, or higher.

It is not altered by the method of cooling, hence its estimation may be made upon any suitably heated specimen cooled in just such a manner as to reveal the grain size in the transformed microstructure.

The cooling schedule for best grain size estimation depends upon the steel composition. Either hypo- or hypereutectoid steels may be cooled slowly enough during the first part of the transformation to cause proeutectoid ferrite or carbide

*Austenitic grain size by fracture rating may not be reliable unless the fracture is in a hardened specimen broken without substantial attendant deformation.

to be rejected in the grain boundaries as a thin network. Eutectoid carbon steels have the grain boundaries nicely marked out by black etching fine pearlite (nodular troostite) in the zone not quite fully hardened. Or in any fully hardened steel a special etch may be given the polished specimen to differentiate by selective attack the separate original austenite grains now converted to martensite.

A close approximate estimate of austenitic grain size in any hardened steel may be made by examining its fracture surface. A chart showing approximate relation between austenitic grain size and either Shepherd or Jernkontoret standard fracture number is included.

Eutectoid or hypereutectoid carbon steels (and even hypoeutectoid alloy steels), usually retain considerable undissolved carbide at low temperatures employed for hardening by best practice. Such austenites are fine grained and are somewhat difficult of estimation as to actual grain size. This is of no serious moment since they are obviously fine and since the carbide-ferrite interface has all the influences upon hardening characteristics that grain boundaries exert.

The grain size to which the interest principally attaches is that established in the temperature range of the operation to be carried out and correlated with grain size effects. The estimation of grain size upon regular pieces heated according to commercial operations up to the time of cooling or quenching is therefore recommended.

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Case Depth Measurement

By R. B. Schenck*

The following discussion of case depth measurement is intended to apply to the more important forms of case hardening and includes cases produced by carburizing, cyaniding, nitriding, combined carburizing and nitriding and by flame hardening and induction hardening.

Case depth is usually determined either by direct measurement or by chemical analysis. Other methods are sometimes employed in special applications, but are of minor importance and will not be discussed in detail.

1. Direct Measurement—This method in its various modifications is the one in most common use and is applicable to any type of case in the hardened state. It is also applicable, with certain limitations, to unhardened cases where a difference in composition distinguishes the case from the core.

All cases, regardless of the method by which they are produced, consist of at least two zones. Three zones are frequently present, such as the hypereutectoid, the eutectoid and the hypoeutectoid zones of carburized steel. This latter is the transition zone in which the hardness of the case decreases to that of the core, or in which the composition of the case approaches and finally becomes the same as that of the core. This transition zone is always present regardless of the process employed and frequently blends into the core so gradually that no sharp line of demarcation can be observed. The usual practice in direct measurement is to measure from the outer edge of the case to the line where the transition zone ends, estimating as accurately as possible in cases where the "end point" is indistinct.

The accuracy of measurement as determined by the distinctness of this "end point" is influenced by a number of factors, such as composition of core, composition of case, previous heat treatment, and method of preparing the sample. Differences in the quenching temperature and the degree of hardening may influence appreciably the apparent case depth. A possible source of error is in the angle at which the specimen is sectioned. It is extremely important that the measurement be made along a line normal to the outer surface of the case.

The several methods in general use employing direct measurement are as follows:

A—Scale Measurement of Rough Fracture—This may be performed either with the unaided eye using a suitably graduated steel scale (preferably in hundredths of an inch), or by means of a low power (10 to 15X) microscope containing a suitable scale. A Brinell microscope answers the purpose admirably. The fractured surface may be either untouched, blued, or etched before measurement. This method applies only to cases in the hardened state.

Untouched fractures can be measured with fair accuracy when the core hardness is sufficiently low to provide good contrast between case and core. Hard cores usually require coloring by either bluing or etching.

Bluing offers an effective method for producing the required contrast. Any means of heating which will develop the necessary temper colors may be employed, such as a lead bath, sand bath, hot plate or tempering oven. An excellent method is to immerse part of the sample in molten lead (1200-1500°F.) leaving the fractured surface exposed to the air. As soon as the color appears the piece is removed from the lead and held until the blue tint deepens on the case area. The sample is then quenched in water to arrest further color change and withdrawn while still warm so that the surface will immediately dry.

Etching is used extensively and produces good results when properly applied. Cold nital is the usual reagent.

B—Scale Measurement of Rough Polished Cross Section—This method employs the same technique as that described under 1-A with the exception that the uncolored surface offers no contrast and must be either blued or etched. Etching is generally preferred for rough polished sections and bluing for rough fractures. Although approximate results can be obtained on unhardened cases, the use of this method is generally confined to cases in the hardened state.

C—Scale Measurement of Highly Polished Cross Section Using High Power Microscope—This is essentially a laboratory method and requires trained personnel. Magnifications of 100X using an eyepiece equipped with a scale graduated in thou-

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Prepared for the Subcommittee on Carburizing. The Membership of the Subcommittee was as follows: R. B. Schenck, Chairman; E. F. Davis, J. A. Dow, R. W. Schlumpf, H. W. McQuaid, and G. T. Williams.

sandths of an inch are usually found suitable for a wide variety of work. As an etching reagent, cold nital will generally answer most requirements.

This method provides greater accuracy than either 1-A or 1-B especially where it is desired to measure the individual zones, or where it is difficult to develop the necessary contrasts as frequently occurs with certain compositions and treatments. Both hardened and unhardened cases can be measured with a high degree of accuracy.

2. Chemical Analysis—In this method successive layers are machined from the surface and subjected to chemical analysis. It applies only where the case is machinable and different in composition from the core, such as work which has been slowly cooled after carburizing or cyaniding. This is strictly a laboratory method and is slow and costly. Its greatest value is in research work.

The following are additional methods which have only limited application and are seldom used:

3. File or drill through the core at right angles to the case until the hardness of the case resists further cutting or abrasion. Measurement of the remaining hard case is taken as the depth. The case on one side must be removed by grinding in order to expose the core. This method is subject to many variables chief among which is the personal equation.

4. Weigh the parts before and after case hardening. This, of course, does not apply to induction or flame hardening. From the increase in weight, the approximate case depth can be determined by calculation.

5. Taper or step grind the hardened sample and determine the hardness at various distances below the surface. This gives a rough approximation of the hardness gradient and the depth of case. This method cannot be used satisfactorily for cases below a certain depth, and where applicable, does not give accurate results due to the effect of the underlying softer metal. It can, however, be used as a specification requirement to control the hardness at a given depth, although it is seldom used for this purpose. Its principal use is in research work.

Magnetic Testing*

Magnetic testing ordinarily applies to ferromagnetic materials: Iron, nickel, cobalt, and their alloys. Magnetic testing of materials used principally for their magnetic properties, such as transformer steels and magnet steels, is done under the same general conditions as will be encountered in service. The limitations of electrical equipment are often determined by the magnetic properties of available ferromagnetic materials. The principles and methods of this type of testing may be found in reference No. 1 or in standard works on electrical engineering.

Magnetic Analysis—Magnetic testing is used also to determine the soundness and mechanical properties of ferromagnetic materials. This type of testing usually is distinguished by terming it Magnetic Analysis. There are many magnetic measurements which can be made quickly and easily, without destruction of the material, and which may be used to test all of the material instead of representative samples. Although numerous factors are involved which influence the magnetic measurements, such as variations in analysis, physical properties, structure, stress, and temperature enough progress has been made to provide commercial magnetic tests for a number of applications. The choice of method of magnetic analysis used in any application depends upon which of the several magnetic characteristics show most variation when the desired property varies. The properties of the magnetization curve and the hysteresis loop may be called the d.c. characteristics of the material. The d.c. characteristics include values of the permeability under different conditions of magnetization, various relations of magnetic induction and magnetizing force, the reluctivity relationship, coercive force, and many combinations of the above. In addition to these, alternating current offers a new set of possibilities. By testing at two or more frequencies it is possible to separate hysteresis and eddy current losses. In the alternating current methods the sample forms the core of a transformer. The various characteristics of the core, particularly those of permeability and watt loss values, provide shifts in the phase angle between the current and the voltage of the induced current and give rise to harmonics in the alternating current wave. By suitably measuring the shifts or the harmonics, any differences occurring in the magnetic characteristics of the cores (or samples) can be distinguished.

Direct current methods are preferable if the fundamental magnetic properties are desired; if it is necessary to secure results at high induction values; or if the samples are large in cross section—in which case excessive eddy currents cause heating and the measurements are predominantly influenced by the surface portion of the samples. The use of a direct current is considered preferable for the detection of deep seated mechanical defects.

Alternating current methods find their greatest usefulness in testing for uniformity of analysis, structure and physical properties. Great sensitivity can be obtained and more variables analyzed. They are most suitable for material of uniform cross section.

Since 1918 the A.S.T.M. has had a committee to study and develop magnetic testing.^{4, 7, 11}

Continuity Tests—Flaws and discontinuities cause an abrupt change in the magnetic field, which when the field of force appears outside the surface is known as "leakage flux." Thus a magnetic field may be set up in the piece either by a current passed through it or by an exciting coil or external magnetic circuit. The leakage flux may be detected by a search coil or by iron filings. In the Sperry rail test¹⁰ a heavy direct current is passed through sections of both rails by a car traveling at a speed of about 6 miles per hour. The rail head is explored by a test coil which gives a record of variations in current density in the rail by measuring the variations in the transverse magnetic field induced by the current. The test is sensitive to flaws to an accuracy of 1% of the cross sectional area of the rail head. Although structural changes, such as those caused by wheel burns, also cause variation of the field, a periodic inspection shows the slow enlargement of cracks and locates a great percentage before they become dangerous.

The powder method (Magnaflux) of inspection^{7, 12} is a special form of continuity test which has come into use in the last few years. It detects surface seams,

*This article was prepared by the Subcommittee on Magnetic Testing. The membership of the subcommittee was as follows: James Allison, Chairman; C. T. Hewitt, H. J. Noble, F. H. Allison, and R. R. Moore.

seams immediately below the surface, grinding cracks, quenching cracks, shrinkage cavities in welds, and incipient fatigue cracks in used machinery. The parts to be inspected are first magnetized, either by passing a current (a.c. or d.c.) through them, or by an external yoke. They are then coated with a finely divided iron powder or magnetic iron oxide, wet or dry. This may be done either while the magnetizing force is being applied or after it has been removed leaving only residual magnetization. Due to so many variables, such as current source and magnitude, and the method and time of applying the magnetic powder, a nonuniformity as to the sensitivity in the test exists as well as in the interpretation of results.

Method of Application of Powder—The dry method consists of dusting the powder on, as from a shaker. The wet method applies either in immersing the work in the vehicle containing the magnetic oxide (immersion method) or in flowing the solution over the work (flow method).

Condition of Magnetism while Powder is Applied—When the part is permanently magnetized and only the residual magnetization is utilized the method is referred to as the residual method. If the powder is applied while the current continues to flow through the work, it is known as the continuous method.

The most important phase of the whole inspection procedure is the magnetization of the piece. The magnetic field created must be at right angles to the defect sought. If the defect be parallel to the flux, no indication will appear. As the angularity of the defect with the flux increases from 0-90°, the indication becomes more strongly apparent. For this reason, irregularly shaped parts must be magnetized in several directions and the powder applied after each magnetization, as second magnetization tends to neutralize the first.

Subsurface defects may be located to a certain extent depending upon size, location, depth beneath the surface, condition of material, and the procedure used. A fair approximation is that a defect may be detected when its depth below the surface is about the same as the cross sectional height of the defect. Present equipment, producing as much as 6,000 amperes with the continuous method, will probably exceed this. Defects on the surface are easily identified by a low amperage with any method of application. The greatest problem in this connection is in evaluating the seriousness of the defect, since different currents and methods produce powder patterns of different intensities.

In another important inspection test, used for such parts as turbine rotor wheels, the material to be tested is passed between the poles of a heavy magnet employing a strong direct current field. Search coils mounted in the pole pieces detect changes of magnetic reluctance of the material due to flaws.

Magnetic Comparison Methods—The correlation of magnetic properties with the composition, physical and structural properties presents a much more complicated problem. The permeameter is used to determine the actual values of the several magnetic properties, as found from the normal induction curve and the hysteresis loop. The normal induction, maximum induction, residual induction and coercive force values of pure carbon iron alloys ranging from 0.13-0.96% carbon content, showing the effect of hardening, tempering, and annealing, have been determined by Cheney.² A thorough discussion of the reluctivity relationship from permeameter tests correlating various tempering treatments after oil and water hardening of a 0.85% carbon steel with magnetic properties has been given by Nusbaum, Cheney, and Scott.³ The results of other permeameter tests correlating chemical and physical properties of metals with magnetic tests are given by Burrows,⁴ and Mauer.⁵ In general the coercive force and hysteresis loss increase as the hardness increases, while the permeability, maximum induction and residual induction decrease.

In addition to variables which influence the mechanical properties, the test is sensitive to unequal stress conditions and differences in temperature in the material, which exert little effect upon the mechanical properties. The effect of stress variation is most noticeable when high frequencies or low magnetizing forces are employed. These tests all serve to compare the material with a standard of known mechanical properties, and care must be used to eliminate variables in the magnetic measurements due to unimportant differences in analysis and structure. Direct correlation of chemical, physical or structural properties with magnetic indications have not yet been successfully established, but within one lot of material of the same general composition and treatment, variations from the indications given by the standard may be correlated and laboratory tests on one sample of a group of pieces showing the same variation will establish the properties of that group.

The simplest form of this test, and the earliest in point of commercial application, is an alternating current bridge in which the impedance of a coil surrounding the test specimen is balanced either against a standard specimen in a similar coil or against a synthetic standard of equal impedance. An alternating current galvanometer or an oscillograph with or without amplification may be used to indicate unbalance; or the current may be passed through a rectifier and measured as a direct current. The balanced alternating current method is usually applied to the testing of large quantities of similar materials, such as razor blade stock, wire, bar stock, and tubing. Certain peculiarities of magnetization may be indicative of seams or other unsoundness. This is particularly true in testing cold worked steel for defects, because the strain appears to enhance the magnetic difference between sound and defective areas. A special coil arrangement representing a modification of the balanced alternating current method has been developed which permits a selective investigation with regard to certain mechanical defects. This coil combination suppresses the effect of differences in material, dimensions or stresses and emphasizes the effect of mechanical flaws such as surface cracks and seams. Analyses and heat treatment variations are now carried out by direct analysis of the emf. induced by the test material. The basic principle used in these measurements represents a modernization of the Joubert¹⁵ point contact method using electronic switching devices and direct current compensation for accurate wave form determinations. Splendid results have been obtained with these apparatus in locating flaws and in determining slight variations in analyses as well as uniformity of heat treatment.

Similar apparatus with special methods of magnetization is used in testing races, balls, and rollers in the ball bearing industry. If the magnetic readings are interpreted in terms of Rockwell hardness variation, reliable average measurements can be made to one-tenth of one Rockwell division. The magnetic indications show irregular internal stress conditions independent of the surface hardness, also variations in microstructure, cracks, soft spots, and shallow hardness.

In certain fields, particularly for small parts of magnetic material, high frequency magnetization is used and a number of types of oscillating circuits have been devised which give valuable indications of slight changes in composition and heat treatment. Tests of this type can also be applied to nonmagnetic materials, measuring in this case the electrical resistivity.

Two specimens having like magnetic properties will have like mechanical properties, but the converse is not necessarily true. Much work has been done, and much remains to be done, to correlate the structural and mechanical properties with resultant magnetic characteristics. The relation between magnetic and other properties is complicated so often by a multiplicity of factors, such as simultaneous variations in chemical composition, heat treatment, mechanical strains, and flaws, that each application must be worked out independently and the testing procedure must be coordinated carefully with mechanical tests.

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The Spark Test

By W. G. Hildorf¹ and C. H. McCollam²

General—The spark test is a method for the classification of steels, according to their chemical analysis, by visual examination of the sparks which are thrown off when the steels are held against a high speed grinding wheel. The test is valuable as a safeguard against the accidental mixing of steels of different analyses, or as a method for separating steels known to be mixed. Spark testing is fast, convenient, economical, and, when applied with proper regard for its limitations, reliable and accurate.

Spark testing is essentially a method for the separation of steels having different analyses. It is not a substitute for chemical analysis, and is not intended for the identification of "unknown" samples. The character of sparks should be similar when spark streams are examined from a number of samples supposedly of the same material. Should one or more of the samples exhibit a spark stream of different character, the presence of "foreign" material is indicated. Chemical analysis can be used in such cases for positive identification.

One of the advantages of the spark test is that it can be applied to steels in practically all stages of production, whether as the billet, as bar stock in the racks, as partly machined forgings, or even in many cases as finished parts. As spark testing is done directly on the pieces themselves, expensive sampling methods with attendant possibilities of mix-ups in numbering and handling are avoided. Small pieces of mixed material which could not be sampled, even if the cost of analysis were not prohibitive, are frequently salvaged, quite economically, by the spark test.

Theory—When a piece of steel is held in contact with a moving emery wheel, small particles of the metal are torn loose. With a high speed wheel, this tearing process is so rapid that the temperature of the particles is raised to incandescence. As they are hurled through the air the trajectory is quite easily followed, particularly against a dark background. This trajectory is called a "carrier line." If the metal is either ingot iron or wrought iron, the result is a small sheaf of single lines, termed a "spark picture." If a piece of carbon steel of about 0.20% carbon is held in contact with the wheel, there will be noted a lightening of the color of the line, and the presence of a number of short single "forks" or "primary bursts," which are due to the presence of carbon (Fig. 1).

While a spark is incandescent and in contact with the oxygen of the air, the carbon present in the particle is burned to carbon dioxide. The transition of solid carbon to gaseous carbon dioxide is accompanied by an increase in volume. Although the particle of hot steel is plastic, it offers resistance to this volume increase, thus building up an internal pressure that is relieved only by an explosion of the particle. There are some observations to support this explanation of the "bursts." For instance, the examination of the incandescent particles when they are cold reveals in the residue numerous hollow spheres with one end completely blown away. The relation of carbon content to the frequency of "bursts" also marks carbon as the element responsible for the forking of the carrier line. A 0.20% carbon steel exhibits a slight forking effect (Fig. 1); a 0.40% carbon steel, a pronounced burst (Fig. 2); and steel in the neighborhood of 1.00% carbon, a minute explosion (Fig. 3). Moreover, greater intensity of bursting is noticed as the carbon content of the steel is increased.

Examination of the Spark Stream—The technique of the visual examination of the spark stream is quite important. When it is properly done, variations in the stream become more readily distinguishable.

Wheel Pressure for Spark Testing—When using the spark cabinet, which will be described later, the operator should hold the pieces on the wheel in such a manner as to throw the spark stream about 12 in. in length horizontally and at a right angle to his line of vision. It is well at this point to spend a little time determining just the right pressure required to maintain a stream of about this length without reducing the speed for most efficient performance of the wheel. Wheel pressure is an important item, whether the piece be held against the wheel, as in cabinet work, or vice versa, because increasing the pressure will raise the

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temperature of the spark stream and bursts, and will give the appearance to the inexperienced eye of a higher carbon content. Experience will later dictate to the trained spark tester the length and volume of the spark stream required for the various steels that will be encountered.

Having determined the proper wheel pressure, it is suggested for the introductory tests that the operator select two steels of widely different carbon content, preferably plain carbon steels. An S.A.E. 1020 and 1050 or higher carbon will do very well. First one, then the other should be held against the wheel, always being careful to strike the same portion of the wheel with each piece. With eyes focused on a point about $\frac{1}{2}$ the distance from the tail end of the stream, watching only those sparks which cross the line of vision, it will be found that after a little while a mental image of the individual spark will be formed. After an operator can fix spark images in this manner he is prepared to examine the character of the "spark picture."

Sections of Sparks—

The entire sheaf of sparks may be divided into three equal sections:

1. The wheel sparks, which are the third of the stream nearest the wheel.
2. The center area.
3. The tail sparks, which represent the third of the stream farthest from the wheel.

The components which are to be observed are the carrier lines, the spark bursts and the "characteristic sparks." The carrier lines will vary in length, breadth, color, and number. The spark bursts will vary in intensity, size, number, shape, and distance from the wheel or from the end of the carrier lines. Carrier lines are the incandescent streaks that trace the trajectory of every glowing particle. They are discussed more fully in connection with the characteristic sparks to which they are closely related.

The Spark Burst—The spark burst, that is, the "carbon spark," is the most useful characteristic of the spark picture, since the variations in the number and intensity of the bursts indicate the changes in the carbon content. Steels alloyed

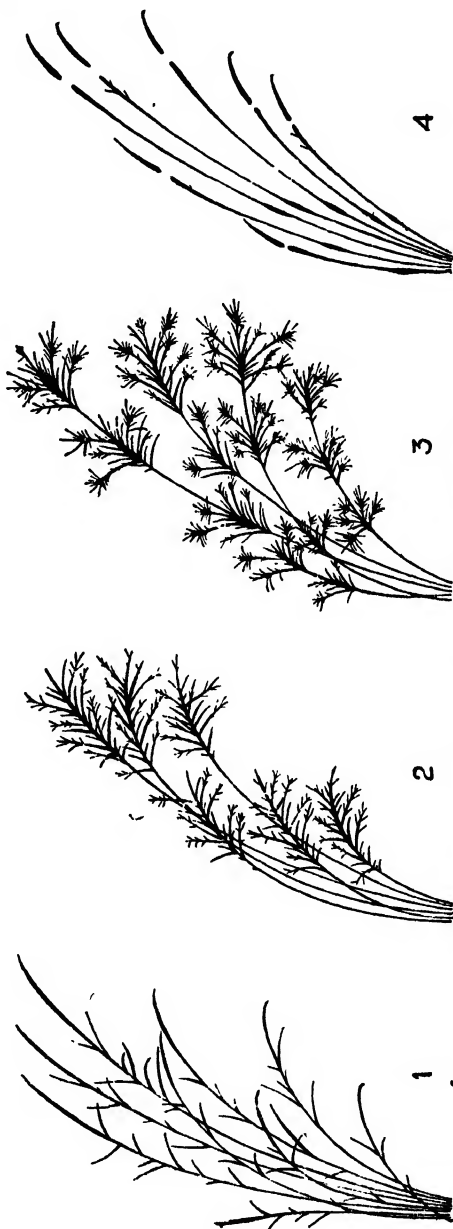


Fig. 1—S.A.E. 1015 Steel, C 0.15%, showing simple "Forking Effect."

Fig. 2—S.A.E. 1045 Steel, C 0.45%, showing "Secondary Burst."

Fig. 3—S.A.E. 1095 Steel, C 1.00%, showing intensity of bursts in the higher carbon range.

Fig. 4—S.A.E. 4615 Steel, C 0.15, Mo 1.75, Ni 1.75, showing a detached "Spear Head" which is characteristic of Molybdenum and the swelling in the spark line indicating Ni with Mo.

differently but with the same carbon content are not always so easily identified. Most of the alloying elements have some influence on the spark picture. They may affect the carrier lines, the bursts, or the form of characteristic sparks. Their effect may be, for example, to retard or to accelerate the carbon spark, or to make the carrier line lighter or darker.

Effect of Molybdenum—The burst is the characteristic spark of carbon. Other elements have distinctive characters. One of the most easily recognized of all the characteristic sparks is that of molybdenum, which appears as an orange colored spear point on the end of every carrier line. Other features of the molybdenum spark are that the spear points are detached from the carrier lines, and that they are always present regardless of the length of the lines (Fig. 4). Sometimes, when the carbon content is high, the spear point is difficult to distinguish; but if a decarburized surface can be found, the characteristic spark immediately becomes quite distinct.

Effect of Nickel—Nickel gives a characteristic spark, identified as tiny blocks of brilliant white light. In low carbon steels (0.10-0.20% carbon and 3.5-5% nickel) these blocks are located in the spark stream quite near the wheel, but in higher carbon steels they are located in the burst. When present with molybdenum, nickel partly suppresses the carbon spark.

Effect of Silicon—Silicon suppresses the carbon spark to a more marked degree.

The carrier line from silicon steels of the S.A.E. 92 series is much shorter than from a plain carbon steel of the same carbon content, and generally ends abruptly in a white flash of light.

Effect of Tungsten—The spark streams for 18-4-1 and molybdenum high speed steels as shown in Fig. 5 and 6 were prepared by J. V. Emmons. He states that, "18-4-2 high speed steel sparks the same as the 18-4-1 type. With light wheel pressure, 4% tungsten steel is similar in appearance to 18-4-1, but with heavy pressure the 4% grade shows an occasional secondary burst not found in the 18% tungsten type. Observations are based on a 9 in. alundum wheel, grade 46M, 1750 r.p.m."

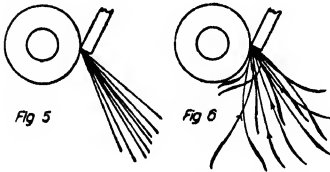


Fig. 5—18-4-1 high speed steel. Red color with numerous red lines.

Fig. 6—Molybdenum high speed steel. Red and orange with numerous orange spearheads with trace of primary bursts.

Equipment for the Spark Test

The Spark Cabinet—A cabinet makes possible the examination of spark streams under ideal conditions. It is convenient both in training men for spark testing and in the examination of spark streams from steels with spark characteristics which are unknown to the operator.

A substantial wood cabinet, about 40 in. long, 36 in. wide, and 36 in. deep will be quite suitable for this purpose. The cabinet should be placed on a bench or table at convenient height for the operator. The inside should be stained a flat black. The interior should have means of artificial illumination. The location of the spark cabinet should be such that no direct light will strike either the operator's eyes or the inside of the cabinet.

The grinder may be mounted in the left front of the cabinet, and should throw a spark stream across the front of the cabinet at right angles to the operator's line of vision.

The Grinder—If the spark stream is to be satisfactory for examination, a spark test grinder should have a peripheral wheel speed of not less than 3500 ft. per min.

If light grinds are to be made on parts in production, the grinding wheels should be of small diameter. If the operator is not to be handicapped by unnecessary fatigue, the weight, bulk, and balance of the grinder are important considerations. Portable grinding equipment of approximately 7 lb. with the weight well distributed has been found very satisfactory. The shaft bearings should be readily replaceable.

The grinding wheels should be rather coarse and very hard and approximately $1\frac{1}{4} \times \frac{3}{8} \times \frac{1}{4}$ in. in size.

Spark Test Goggles—Eye protection during spark testing is very important, both in avoiding injury from steel and emery particles, and in minimizing the

effects of certain light rays. Goggles which satisfy these requirements have been developed for spark testing by some of the optical companies.

Standard Spark Test Samples—Standard samples can be prepared from bar steel. A convenient size is 1 in. in dia. and 3 in. long. One end should be stamped with the identification marking of the steel and a sample number. Chemical analyses of these samples should be kept for reference. Samples should cover as wide a range of chemical compositions as possible, to permit the operator to familiarize himself with the manner in which the character of sparks is affected by various carbon contents and alloying elements.

For training purposes, a dozen or more samples should be cut from bars of the material with which the spark tester will have occasion to do most of his work. For example, if experience in identifying the molybdenum spark is desired, a dozen pieces of S.A.E. 1020 in 1 in. round steel, stamped "1," and a dozen pieces of S.A.E. 4615 of like size and appearance, stamped "2," will provide the standard samples necessary. These standard samples are consulted only as a means of verifying the correctness of the classification of the "unknown" samples.

Spark Testing Personnel—Thought should be given to the selection of personnel for spark testing. It is advisable to select a man whose eyes are light sensitive and whose manner is alert. He should have a fair knowledge of the composition of various steels.

The operator should be given every opportunity to practice spark testing. Given the necessary physical and mental attributes, a spark tester's efficiency becomes a matter of experience in the examination of sparks. The more rapidly that experience is acquired, the sooner he will be available for duty.

In connection with spark testing personnel, it is advisable to have strict supervision of the work. The spark tester should be held at his highest possible efficiency. It must be understood by each operator that his work must be 100%, that not a single piece of foreign steel can be passed in error. Decisions must occasionally be made as to when the spark test can be used safely, and also when it definitely must not be used. The reputation of the spark test for reliability will depend largely upon the wisdom of such decisions.

Plant Spark Testing—Proper lighting conditions are a very necessary adjunct to satisfactory spark testing.

The presence of strong direct light, either natural or artificial, is a distinct disadvantage. Spark testing should be done in a shadow, and against a dark background.

It is advisable to protect the spark stream from heavy drafts of air as this will cause a very definite hooking of the tail sparks, which may be confusing.

Bar and tube stock, carefully racked, can frequently be spark tested without removing from the racks. Similar material in bundles can be spread out on inspection benches. Small pieces of regular size and shape are generally placed on work benches. If a large number of pieces must be tested in a limited time, laborers can be used to arrange the parts in uniform rows for the spark tester, so that his time can be applied entirely to spark examination.

Care must be exercised in the case of hot rolled or heavily scaled material to be certain that the spark stream is not from a decarburized area. Bar stock is more safely ground on the cut end, and forgings at the point from which the tonghold was removed.

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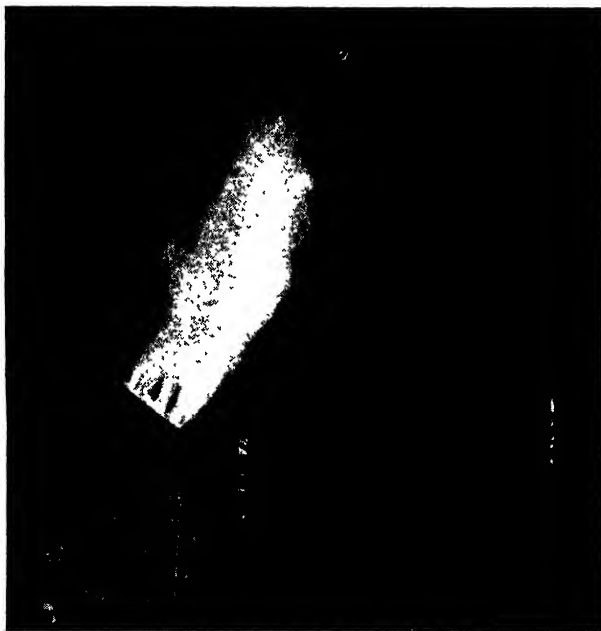
The Bessemer Process of Steel Making*

By Dr. G. B. Waterhouse

History—The invention of the Bessemer process of steel making was a great event in the world's economic history. Up to that time steel was scarce and expensive, being made chiefly by the crucible process. It was reserved for special purposes so wrought iron, cast iron, and bronze were used for structures, engines, and ordnance. Henry Bessemer developed the process in the search for an improved material for guns. He started his experiments late in Dec., 1854, shortly before his 42nd birthday. The first public description of the process was in Aug., 1856, before it had been perfected. Many difficulties were afterward encountered principally due to phosphorus in the pig iron used as the raw material.

Application for a patent disclosed that William Kelly had worked on a similar method since 1847 and a patent was granted to Kelly in 1857. The patent controversy was ended in 1865 after which time developments were rapid, mainly due to the energy and genius of the great engineer, Alexander Lyman Holley.

Description of Bessemer Converter—Molten blast furnace iron (pig iron) of the proper composition is poured into the Bessemer converter, which is a pear



A Bessemer blow.

shaped steel vessel mounted on trunnions. The converter is tilted to receive the metal. The charge varies from 5-30 tons. The lining of the converter is of acid refractory material, the slags produced consist of more than 50% silica so the process is known in this country as the "acid Bessemer." When the vessel is charged, air is admitted from the blowing engines or turbo-blowers through one of the trunnions, which is hollow, to a blast box at the bottom of the converter. From this box the air passes through numerous holes or tuyeres, $\frac{1}{2}$ - $\frac{3}{4}$ in. dia., to the interior of the converter. The blast pressure is about 20 psi. These converters are known as bottom blown, and this article will not describe the process carried out in side-blown converters used in foundries for making steel for castings. These vessels are

often called baby Bessemer (Tropenas Converters) and usually vary from $\frac{1}{2}$ -3 tons.

Operation of Bessemer Converter—After the blast is turned on the vessel is slowly turned upright. The air blows through the charge and oxidizes (in the order given) the silicon, manganese, and carbon. The combustion of these materials, especially silicon, and some of the iron furnishes the heat to carry on the process. The progress of the operation is shown by the flame issuing from the mouth of the converter. At first the flame is short and dry with very little visibility, followed by a reddish-brown flame of low luminosity occurring during the

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The personnel of the Subcommittee on Melting was as follows: G. V. Luerssen, Chairman; G. A. Dornin, J. P. Gill, Dr. C. H. Herty, Jr., O. K. Parmiter, and Dr. G. B. Waterhouse.

period of silicon and manganese oxidation. Then as the carbon burns it changes in character and increases in size. It becomes yellowish-white and reaches about 30 ft. in height. When the flame drops, which it does in a characteristic way at the end of the blow, the vessel is again turned down on its side and the blast shut off.

This whole operation or "blow" usually takes from 12-18 min. The material is now known as "blown metal." It contains traces of silicon and manganese and 0.06% or less of carbon. Substantially all the phosphorus and sulphur of the original pig iron are present in the blown metal which also contains about 0.2% of oxide of iron, FeO . This last constituent makes the metal red short, incapable of being successfully forged or rolled, so that some deoxidizing agent is added to the blown metal. When making soft or low carbon steel the usual addition is ferro-manganese. This is crushed to egg size and added to the blown metal while it is being poured from the converter into the ladle, after which the ladle is swung or carried over the ingot molds and the ingots poured. The final soft steel would show about 0.08% carbon, 0.38% manganese, 0.10% phosphorus, 0.045% sulphur and traces of silicon. The whole operation is brief and the liquid pig iron is very rapidly converted into liquid steel.

Raw Material for Converters—The main raw material is liquid pig iron. This is usually brought from the blast furnace or furnaces in ladles and poured for storage into containers known as mixers, because various casts are mixed or averaged. These mixers hold from 200 to as much as 1200 tons. They are of steel construction, lined with fire brick or other refractory material and can be rotated by electricity or hydraulic power. Metal is poured from the mixers when needed through a spout into a ladle standing on a scale. When necessary, the mixers are heated by means of gas, oil, or tar. The heat supplied is just about enough to offset radiation losses. Care is taken to prevent blast furnace slag entering the mixers with the iron, as it would cause slopping and bad working in the Bessemer converter.

The composition and amount of iron entering the mixer is very important to the Bessemer blower. For good practice the pig iron is held within fairly close limits.

Silicon is the most important element and varies from about 1.00-1.80%. It should be held as constant as possible and at the particular amount found to work best for the individual shop.

The total carbon does not vary much in iron for the Bessemer converter. It is not reported usually and varies from about 3.80-4.00%.

The manganese usually runs under 0.60%. It should not run much higher as high manganese makes a thin slag in the converter which slops out of the vessel on to the floor of the shop and causes trouble, as well as loss of steel, and handicaps the blower in producing steel of given analysis.

Phosphorus in the iron varies from about 0.085-0.100%. Substantially all of the phosphorus in the pig iron remains in the blown metal and in the finished steel. It must be low enough so that the final steel is not above the required amount which in general is 0.110%, although some specifications allow a maximum phosphorus content of 0.13%. This is the reason why iron ores are classed as Bessemer and Non-Bessemer, the Bessemer ores being so low in phosphorus that the blast furnace iron made from them is low enough to be used in making Bessemer steel. Incidentally all the phosphorus entering the blast furnace with the charge is reduced and enters the liquid iron.

The sulphur usually runs about 0.04% and varies from 0.03-0.08%. Both phosphorus and sulphur are about 8% higher in the finished steel than in the blast furnace iron, due to loss in weight and concentration.

Bessemer Losses—In ordering the proper weight of liquid iron from the mixer to make a heat of steel the blower allows for the weight of scrap he will use and the loss in weight during blowing. This loss in weight is fairly constant, depending on various factors, chiefly the composition of the iron, because silicon, manganese, and carbon are practically all oxidized together with a certain amount of iron. The loss is usually from 8-10%.

Temperature Control—After the liquid iron has been poured into the vessel, the blast turned on and the vessel turned upright, the scrap chute is swung into the nose of the vessel and the correct amount of scrap added. This scrap addition

is a method of temperature control, which is the most important part of a blower's duty.

The finished steel in the ladle must be at the proper temperature for the grade of steel being made. It must pour cleanly from the ladle into the ingot molds so that the ingots will set properly. If too cold a large skull will be left in the ladle and there may be trouble in pouring the ingots. If too hot the internal structure of the ingots will not be correct and surface as well as interior defects may develop during rolling.

In general, the blower tries to control his temperature so that a small skull is left in the ladle after pouring the finished steel. There are two methods available to him to reduce temperature. One is by the addition of scrap, the other is by using steam admitted with the air. Bloom butts, or crop ends of steel weighing about 100 lb. are generally used, but sometimes cold pig iron is employed. Only about 15% by weight of the liquid iron can be used, so the Bessemer is not a scrap-using process.

The composition of the liquid iron is generally maintained to give a reserve of temperature, so scrap or steam is generally needed. Occasionally cold heats are encountered. If known in time ferrosilicon can be added with the liquid pig iron, or added down the scrap chute, or the vessel can be blown on its side so that part of the air rushes over the surface of the metal. This causes excessive loss of iron, but does raise the temperature.

Additions—In making most of the steels listed in Table I ferromanganese is added while the blown metal is being poured into the ladle. This brings about deoxidation and adds the required amounts of carbon and manganese to give good rolling and working properties and meet the specifications. There is a loss of manganese during this operation of about 35%. This loss is allowed for and experience soon shows the correct weight of ferromanganese to be added. The sulphur needed for the free cutting steels is added to the converter in the form of pyrites or to the converter or ladle as stick sulphur in a strong paper bag. There is a loss of about 45% of the sulphur added.

In the case of the higher carbon steels the proper weight of liquid iron is brought from the mixer and added to the blown metal in the converter. Many times the blast is turned on and the vessel is turned up and down again to give a "puff" and thoroughly mix the materials, then ferromanganese is added as usual while being poured into the ladle. Sometimes the required carbon is obtained by adding dry crushed anthracite or coke in bags to the blown metal while being poured from the converter.

Rail steel, and other high carbon steels, were formerly made by adding a molten mixture of spiegeleisen and pig iron to the blown metal in the converter. This mixture was first melted in cupolas and carefully calculated to take care of losses. The requisite amount of carbon, manganese, and silicon, was added and the correct weight was tapped from the cupolas. Almost any grade of carbon steel can be made by the Bessemer process, if the use of steel high in phosphorus can be allowed.

Composition of Bessemer Steel—During the first part of the blow, silicon and manganese are rapidly oxidized and enter the slag. This is characterized by a short dry flame. The flame then turns to a yellowish-white as the carbon is oxidized and begins to increase in size until it is 25-30 ft. in height. At the end of the blow there is a well marked drop of the flame and the vessel is turned down. The heat may be turned down green or it may be "full blown," depending on the steel to be made.

The blown metal contains from about 0.04-0.10% carbon, traces of manganese and silicon, phosphorus from about 0.085-0.110%, and sulphur about 0.03-0.07%, except in cases where sulphur has been added in the vessel. The additions required to make the finished steel are added usually in the ladle or else in the vessel and in the ladle.

Typical analyses of finished steel are shown in Table I.

Table I does not include bars, small structural shapes, and materials for railroad purposes, such as spikes, bolts, and nuts, for which considerable Bessemer steel is used. The analysis of steels for these purposes does not vary greatly from

Table I
Composition of Bessemer Steel

Material	Carbon %	Manganese %	Phosphorus %	Sulphur %
Soft Bessemer Steel Grades				
Skelp	0.10 max.	0.30-0.60	0.11 max.	0.08 max.
Sheet and tin bar	0.10 max.	0.30-0.50	0.11 max.	0.07 max.
Soft wire	0.08	0.30 max.	0.11 max.	0.08 max.
Medium wire	0.08-0.12	0.30-0.50	0.11 max.	0.08 max.
Hard wire	0.12-0.17	0.70-1.00	0.11 max.	0.08 max.
Ordinary screw stock	0.08-0.13	0.70-1.00	0.09-0.13	0.10 min.
A.S.T.M. screw				
S.A.E. 1112/stock	0.08-0.16	0.60-0.90	0.09-0.13	0.10-0.20
Special Grades Screw Stock				
Special	0.08-0.16	0.75-1.10	0.09-0.13	0.20-0.30
High carbon screw stock	0.25-0.35	0.60-0.90	0.09-0.13	0.075 min
Reinforcing Bars				
Reinforcing bars	0.15-0.35	0.70 max.	0.11 max.	0.08 max.

that shown for skelp and sheet bar except that as a rule only the phosphorus is specified and tensile test requirements are imposed. In many of these steels, especially those exposed to atmospheric corrosion, copper is present from 0.20-0.30%, and has been found to be very helpful.

Application—The main uses of Bessemer steel are indicated in Table I. They include skelp for making lap welded and butt welded pipe, especially the smaller sizes, sheet bar for rolling into sheet for tin plate and galvanized material, bars and special shapes for free machining purposes, especially automatic screw machine products and wire products of many different kinds. The Bessemer process is the second steel making method of the country in regard to tonnage. Its capacity is about 11.5% of the total steel making capacity and for the last few years the steel made by this process has varied from 11.5-12.8% of the total steel made. It has shown a declining tendency until recently, being 33% in 1912 and dropping to 11.6% in 1931 and increasing somewhat since that time.

Also considerable steel is made by a combination of the acid Bessemer and the basic open hearth process, which is called the Duplex Process, the steel being known and shipped as open hearth steel. One other application of the Bessemer process is the Aston process of making wrought iron.

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The Open Hearth Process*

By Dr. C. H. Herty, Jr.

Origin of the Open Hearth—The first steel made in any considerable quantity was produced by the crucible process, invented by Huntsman in 1740. Puddling furnaces were patented in England by Cort in 1784 and Great Britain rapidly took the lead in iron making. Bituminous coal was used in these furnaces.

In 1855, Sir Henry Bessemer patented the Bessemer pneumatic process for manufacturing steel, and in 1856 Dr. C. W. Siemens and his brother Frederick obtained patents on a regenerative furnace. These two patents were destined to revolutionize the steel world, the former by enormously increasing steel tonnage and the latter by providing for temperatures so high and so constant that the tonnage from regenerative furnaces at present far surpasses that produced by the Bessemer process.

In 1864, Martin successfully operated, with the assistance of Dr. Siemens, a regenerative furnace for melting steel. The open hearth process as developed by these gentlemen was called the Siemens-Martin process and the fundamentals of their process are in common use today. It must be stated that the open hearth process did not originate with Martin or Siemens, as J. M. Heath in 1845 proposed this method. His attempt failed as the necessary temperature could not be obtained.

Henderson in 1870 and Snelus in 1872 suggested the use of lime as a dephosphorizer for iron, and Thomas and Gilchrist in 1877 used a basic lining in a Bessemer converter. Basic linings were put into use in open hearth furnaces and the process at once came into favor. In the acid open hearth process, referred to later, neither phosphorus nor sulphur may be eliminated; this process is therefore confined to the melting of raw materials low in these two elements.

The Basic Open Hearth

The Necessity for Refining Pig Iron—Pig iron as produced today for the basic open hearth process has the following approximate percentage composition: C, 4.00; Mn, 1.70; P, 0.25; S, 0.04; Si, 1.00; Fe, 93.00.

As this material is unfitted to fill the needs for which steel is used, it must be refined. Refining consists of the removal of carbon, manganese, phosphorus and silicon by oxidation and the removal of suspended oxide material and gases by scrubbing. It is necessary to supply a strong base which will form stable compounds with the oxides of phosphorus and silicon and with sulphur and hold these permanently in the slag—which is the molten magma formed when the lime and various oxides unite with or dissolve in one another.

The Open Hearth Furnace—Figs. 1 and 2 show in cross section a sketch of an open hearth furnace. The basic furnace consists mainly of a shallow, elliptical shaped vessel lined with some suitable basic refractory. This hearth is covered with a silica roof forming a combustion chamber, and the steel is made on the hearth of the furnace. Suitable spaces are left for doors on one side of the furnace through which the operations may be controlled.

The hearth is usually lined with magnesite brick and covered with a mixture of burned magnesite or dolomite and open hearth slag. The bottom may be kept in repair with dolomite or in extreme cases with ground magnesite or chromium ore. The average consumption of dolomite for repairing is about 35 lb. per ton of steel.

In many modern furnaces the backwall slopes at an angle instead of being built straight as in Fig. 1. This sloping backwall prolongs the life of the furnace as the flame cannot cut the brick as readily as it can with the straight backwall; the construction also facilitates repairs.

In the rear of the furnace, at the center and bottom of the hearth, is the tap hole. This is between 4 and 8 in. in dia., depending upon the size of the furnace and type of practice. During the steel making period this hole is filled with a suitable refractory material which may be easily removed when the heat of steel is to be tapped. In a tilting furnace the tap hole is put in above the level of slag and metal and the furnace tilted when it is desired to withdraw the metal.

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Open hearth furnaces are usually of the regenerative type, in which the hot gases are passed through checker chambers and transfer heat to the brickwork. From time to time, say every 15-20 min., the flow of gases through the furnace is reversed and cold air enters the hot chambers and is heated to about 2400°F., which promotes fuel economy and temperature control.

Some fuels are preheated in the checkers before they enter the furnace, others are not. The fuels preheated are producer gas, and mixtures of blast-furnace and coke oven gas. Tar and oil are brought directly to the port and atomized with high pressure steam or air. They are preheated to about 300°F. to increase the fluidity for atomization. Natural gas and coke oven gas are delivered to the port direct. The port must be designed differently for each type of fuel.

Charging the Furnace—The scrap, cold pig iron, limestone, and ore are loaded into charging boxes. A charging machine picks up the individual boxes and charges the contents on the hearth of the furnace. In a charge consisting of limestone and scrap, the limestone is placed on the hearth first, followed by the scrap, until the charging is completed or the furnace is full. If large amounts of light scrap are being charged, it is often necessary to fill the furnace, melt down the scrap somewhat, and then finish charging the scrap. It is sometimes advisable to charge a layer of scrap on the hearth of the furnace before charging the limestone, particularly if the limestone tends to stick to the hearth too much. If ore is charged, it is generally added before the limestone or just after the limestone, depending on the condition of the bottom. Charging ore first tends to cut out the bottom. When cold pig iron is used, it is usually charged after the scrap. If hot metal (molten pig iron) is used, and the largest tonnage of steel is made by this method, it is brought to the furnace in a ladle and poured through a spout inserted in one of the charging doors. The hot metal addition is made after the scrap has melted down somewhat and after the furnace has become well heated.

The analysis of the steel scrap should be known because copper, nickel, and molybdenum can be diluted but not eliminated from the metal. Tin, zinc, lead, and antimony are detrimental to the quality of the steel, and so should be avoided.

Melting the Charge—During the period between the charging of the scrap and the hot metal addition, there are two chemical reactions taking place in the bath: (1) The oxidation of the scrap while it is melting; and (2) the calcination of part of

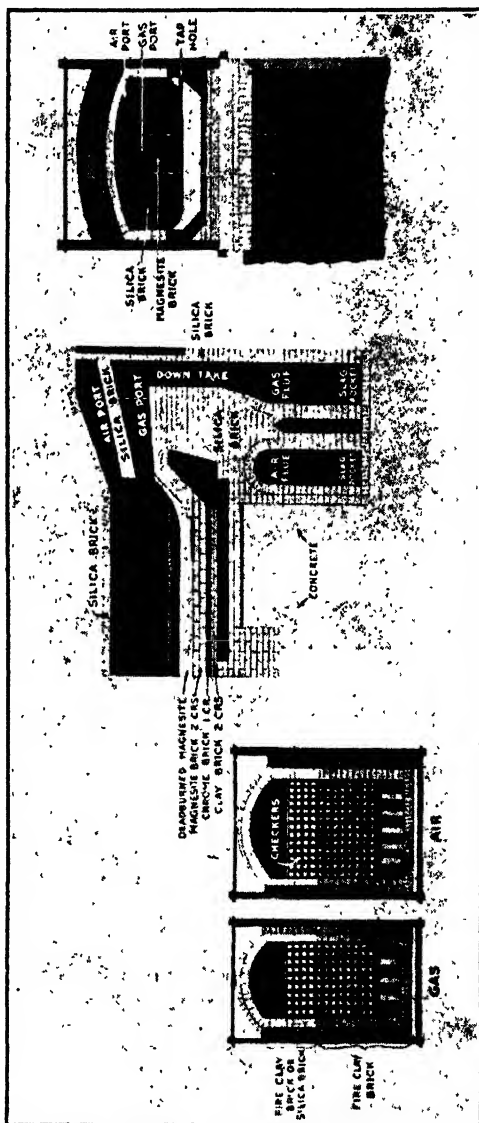


Fig. 1—Typical open hearth furnace.

the limestone. As soon as the hot metal is added, a great deal of the scrap and all of the limestone are submerged in liquid metal. The oxidation of the exposed scrap proceeds until sufficient scrap has melted to raise the level of the liquid

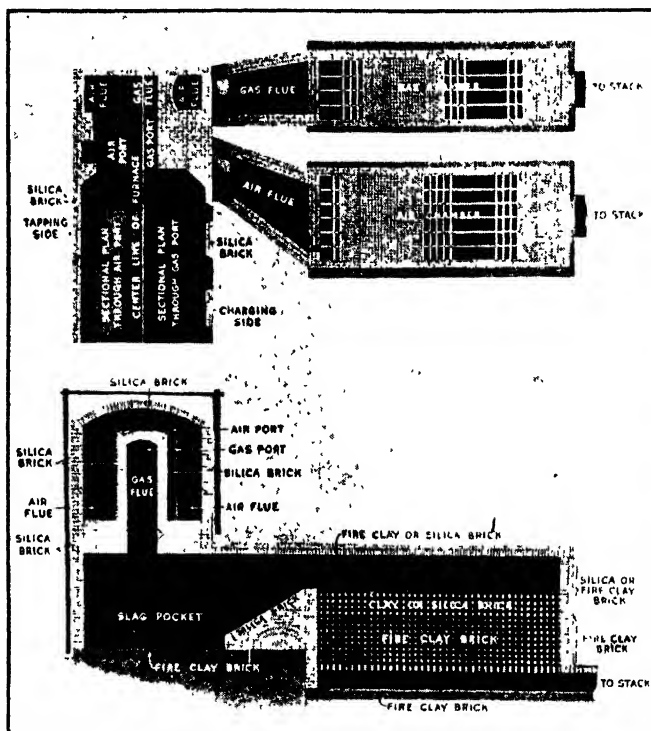


Fig. 2—Typical open hearth furnace.

metal enough to cover up all solid material. During this melting period large amounts of carbon dioxide are being evolved from the calcination of the limestone by the reaction:



There is a heavy boiling action caused by the CO_2 evolution, and at the same time this gas reacts with the liquid iron to form iron oxide.



As the scrap continues melting, pieces of limestone which have been held on the bottom by the scrap begin to rise through the metal bath and float in the slag. The period in which the lime is coming up is known as the lime boil, and the agitation from the gas evolution assists materially in the transfer of heat from the fuel to the bath because the hot upper layer of metal is thoroughly mixed with the colder lower layers.

Function of Slag in the Steel Making Process—As it is necessary to remove carbon, manganese, phosphorus, and silicon as oxides, and in order to prevent phosphorus from reverting from the slag into the metal during the latter stages of refining, it is necessary to carry a large percentage of lime in the slag to form a stable calcium phosphate. The slag floats on the surface of the bath, and it is through the iron oxide content of the slag that a large amount of the removal of metalloids (C, Mn, P, Si) by oxidation is carried out. The slag thus acts as a regulator of oxidation and as a carrier of undesirable impurities. If the slag is weakly basic, considerable erosion of the furnace lining will take place. If

the slag is too basic it is generally very viscous and the reactions taking place will be slowed up considerably. From the best data available at the present time, the slag is evidently calcium silicate, $\text{CaO} \cdot \text{SiO}_2$, and $2\text{CaO} \cdot \text{S} \cdot \text{O}_2$, containing dissolved CaO , $3\text{CaO} \cdot \text{P}_2\text{O}_5$, MnO , FeO , CaS and CaSO_4 . The magnesia in open hearth slags is generally held to be suspended as periclase (MgO), in which some iron oxide may be dissolved.

It is very desirable that the slag have a given consistency during the working period, as the oxidation of the bath is controlled not only by the amount of iron oxide in the slag, but also by the rate at which iron oxide diffuses from the slag into the metal, and this diffusion rate is a function of slag viscosity. If the slag is too viscous it may be thinned out by the addition of fluorspar, and if the slag is too thin (too fluid) it may be thickened (made more viscous) by additions of burnt lime or burnt dolomite.

The Formation of the First Slag—During the initial melting period, a large amount of iron oxide is formed by the oxidation of the scrap. This combines with some of the calcined limestone on the hearth of the furnace and with some of the dolomite on the banks to form a slag high in iron oxide and lime. As soon as the hot metal is added, the slag formed during melting reacts with the metalloids in the pig iron, and silicon and manganese are very rapidly eliminated. The result of the reaction of these two metalloids with the iron oxide in the slag is a sharp decrease in the iron oxide content of the slag and a rapid increase of SiO_2 and MnO in the slag. These slags are weakly basic, and the result is a severe erosion of the furnace banks by this initial slag. If high silicon pig is used this corrosive action is intensified. If the pig iron used is unusually high in phosphorus a tilting furnace is used, so that slags may be readily drawn off.

The composition of the slag at the time the heat is melted has a very pronounced effect on its oxidizing power during the finishing period of the heat. The reason for this is that a great deal of the oxidation takes place through the action of the furnace gases on the FeO in the slag, and the higher the FeO in the liquid slag the greater will be the oxidation throughout the heat.

Working the Heat—After the heat is melted a test is taken out of the furnace and the carbon content estimated by the appearance of the fracture. From this fracture the furnace operator judges how much ore should be added to eliminate the carbon to the desired point. The ore is introduced either by shoveling or in a charging box, and a lively reaction at once proceeds because of oxidation of the carbon. As the carbon is being eliminated, steel tests are sent to the laboratory for carbon analysis, or the operator estimates the carbon content of the bath by a fracture test. While the carbon is being eliminated, the operator attempts to "shape up" his slag so that at the finishing period the slag is of a creamy consistency and the metal at the proper temperature. The temperature of the bath is judged by stirring a rod through the heat and noting the appearance of the end of the rod when it is withdrawn from the furnace, or by pouring a test and noting the tendency of a skull (solidified crust) to form in the spoon, and also by noting the fluidity and nature of the steel while pouring. The temperature of the bath is regulated by the amount of fuel used, and this is generally under the control of the operator. If the amount of fuel used is kept constant, the temperature of the bath will be influenced by: (1) The amount and viscosity of the slag; (2) the degree of agitation; and (3) the chemical reactions in the bath, which may or may not influence the second factor. All of these factors are to some degree under the control of the operator and must be considered in securing the desired bath temperature. In some of the newer installations of open hearth furnaces the fuel regulation is determined by automatic control of checker temperatures, thus eliminating to a large extent the personal element in the judgment or misjudgment of steel temperature.

Finishing the Heat—Unfortunately, during the process of elimination of metalloids by oxidation, a considerable amount of iron oxide dissolves in the steel bath, and before the steel can be poured into the molds it is necessary to either partially or fully deoxidize the steel. This deoxidation is carried out either in the furnace, the ladle, or the molds. For so-called quality steel, as much deoxidation as possible is done in the furnace, because the elimination of nonmetallic matter resulting from deoxidation depends to a considerable extent on the distance the inclusion must rise before leaving the metal. Inasmuch as the average depth of the steel bath is about 30 in. and the average height of a ladle about 12 ft. it is obvious that if

the deoxidation is done in the furnace less time will be required for the elimination of nonmetallic matter than if the deoxidation is carried out in the ladle. On the other hand, when the steel is deoxidized in the furnace, if the heat is held in the furnace to allow nonmetallic matter to rise out of the steel, iron oxide will diffuse from the slag into the steel.

Inasmuch as the slag-metal area in the furnace is much greater than in the ladle, it is evident that more iron oxide will diffuse back from the slag in the furnace than from the slag in the ladle. There is, therefore, a balance between deoxidation in the furnace and ladle, but by properly regulating the viscosity of slag and its iron oxide content, it has been found that it is better to deoxidize in the furnace than in the ladle. Some deoxidizing additions must be made in the ladle on account of the oxidizing conditions in the furnace. Thus, if a heat is being deoxidized with ferromanganese and ferrosilicon, it is customary to add ferromanganese in the furnace and ferrosilicon in the ladle. The choice of deoxidizers and the manner of deoxidation are extremely important in making the best steel from a given open hearth heat at the time the steel is ready to be deoxidized. In some cases the steel is deoxidized in the mold, but this is generally a poor practice for making high quality steel. For certain types of steels where the specifications, particularly for cleanliness, are not rigid, this practice is very satisfactory in that it is by far the cheapest of any deoxidation method. In general, aluminum is the only deoxidizer used in the molds. Ferrosilicon is used in some grades of steel, but this is the exception rather than the rule.

The time consumed in making a 100 ton heat of open hearth steel is about 11 hr. and is divided as shown in Table I.

Killed, Semikilled, and Rimmed Steels—From the standpoint of the user, there are three classes of plain carbon steels with which he must deal: (1) Killed steel; (2) semikilled steel; and (3) rimmed steel. All forging grade steels and in general all steels above 0.25% carbon are killed. Structural steels from 0.15-0.25% carbon are killed or semikilled, and most steels below 0.15% carbon are rimmed.

Killed Steel—In forging grade and other high carbon steels, the essential quality of the steel is soundness (freedom from blowholes and segregation), because this material generally goes into a product where definite strength factors are desirable. The term "killed" indicates that the steel has been deoxidized sufficiently so that the metal when poured into an ingot mold lies perfectly quiet. In killed steel there is no evolution of gas, and the top surface of the ingot solidifies almost immediately. This condition is brought about through the proper additions of ferrosilicon, aluminum, and other strong deoxidizers.

In making killed steels general practice is to catch the heat coming down—that is, to eliminate the carbon to the desired analysis and then tap the heat. It is preferable to leave the heat in the furnace for at least 10-20 min. after the addition of the deoxidizer, as this length of time is necessary to insure proper mixing of the furnace additions and elimination of nonmetallic matter.

Semikilled Steel—In making semikilled steels the heat is caught coming down at the desired carbon content, and the manganese is added either in the furnace

Table I
Division of Time for Making 100 Ton Open Hearth Heat
Total Time, 11 Hr.

Operation	% of Time
Start of charge to end of charging.....	19.0
Actual time spent in charging.....	6.0
Start of charge to hot metal addition.....	35.0
Finish charging scrap to hot metal addition.....	15.0
Duration of lime boil.....	27.0
Working the heat.....	23.0
Deoxidation to tap.....	1.0-5.0 ^a
Tapping	1.0
Finish tap to start of repairs on banks.....	1.0
Repairs on banks and bottom.....	2.0
Finish of tap to start of charging.....	4.0

^aSome of the items in the above table overlap others, making the total percentage greater than one hundred.

^bFor rimmed and semikilled steel.

^cFor killed steel.

or in the ladle. If silicon is used, it is added in the ladle as 50% ferrosilicon. When aluminum is used it is sometimes added in the molds, although in most plants additions of aluminum are made both in the ladle and in the molds.

Rimming Steel—Clean low carbon deoxidized steels are very difficult and costly to make in the basic open hearth so recourse is had to the process called rimming in which the steel is partially deoxidized with manganese, either alone or with some other deoxidizer. When the metal begins to solidify there is a brisk evolution of gas which cleanses the surfaces of the growing crystals. The result is a skin of very clean metal. The depth of this skin varies with the skill of the steel maker. When the metal has cooled to the point where solidification proceeds throughout the liquid a great deal of the gas is trapped and a porous interior results. In making rimmed steel the effort of the steel maker is to obtain the proper rimming action in the molds, as this rimming action determines to a large extent the solidity of the surface of the ingot. This rimming action is obtained by a close control over the iron oxide content of the slag, the slag viscosity, the temperature at which the heat is poured, and the deoxidizers used.

The advantage of the rimming steel practice is that the outside surface of the ingot is quite clean and low in carbon. These factors give an excellent surface to the finished product. A wide variety of steels for deep drawing, where ease of forming is the major consideration, are made by the rimming process.

The Acid Open Hearth Process—In the acid open hearth process the lining of the furnace is of silica sand, an acid material. As any basic material in the slag would tend to attack the lining rapidly, the acid process is confined to materials low in sulphur and phosphorus as these two elements require the presence of lime for their elimination.

In an acid slag a large part of the iron oxide is combined with silica as silicate of iron and manganese. This combined iron oxide will not diffuse into the metal, nor will it be oxidized readily by the furnace gases. Therefore, for a given total iron oxide in the slag, the metal will be much less oxidized in the acid open hearth furnace than in the basic open hearth furnace, and consequently there will be fewer products of deoxidation to be removed.

One of the most important advantages of the acid process over the basic is the fact that the composition and nature of the slag can be controlled almost at will.

A typical acid slag analysis in per cent is: FeO, 15; MnO, 21; SiO₂, 53; CaO, 4; and small amounts of Al₂O₃, Cr₂O₃ et cetera. The per cent of FeO + MnO is automatically regulated by the fact that iron manganese silicates will dissolve up to about 60% of SiO₂ from the furnace banks. By regulating the amount of MnO in the slag the FeO can be closely controlled. Thus the operator is enabled to control more consistently the quality of the steel being made.

The acid open hearth process is used almost entirely for the manufacture of killed steel. A very small tonnage of rimmed steel is made by this process.

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The Melting of Tool and Other High Grade Steels in the Basic Electric Furnace

By J. P. Gill*

History—The first attempt on record to melt steel electrically dates back to 1878 when Siemens conducted his initial experiments with arc melting in a small crucible. During the next 20 years progress in electric melting was slow, and probably the most noteworthy event in this period was the development by Heroult about the year 1890 of a furnace for the production of ferroalloys. Beginning with the year 1900, the development of electric furnaces gained momentum, and several types of both arc and induction furnaces were placed on the market. The most promising one of these was the so-called direct arc type devised by Heroult and finally put into production in this country about 1906. Consequently the history of electric melting of tool and other high grade steels in the United States dates back only about two decades.

The first furnaces were relatively crude affairs, but both the mechanical and electrical features were greatly improved and perfected during the following ten

years, and the introduction of automatic control, modifications to facilitate charging, improvements in electrodes, increase in power input, and finally the introduction of multi-voltage transformers have made the arc furnace an entirely practical tool. Along with the development of the furnace has come the development of improved melting practice. Originally the electric furnace was designed to make tool steels and special alloys which were then made by the crucible process, but its field rapidly broadened to fill the need of new requirements in special ordnance steels and automotive alloy steels.

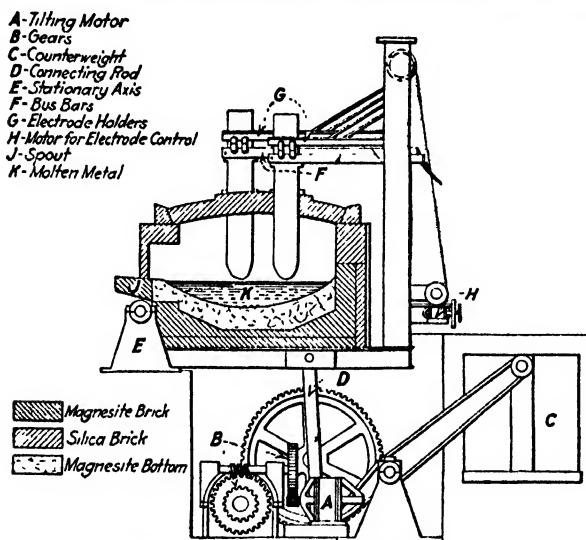


Fig. 1—Electric melting furnace.

There followed naturally a further development of the process along economic lines, resulting in a diversity of practice, such as the cold melt process used in the manufacture of tool steels and the finer alloys, and the hot metal, or duplex process, often used in tonnage electric practice.

There is consequently a considerable difference in melting practice between the different units of the tool and alloy steel industry, and it would be an impossible task to give here more than a general outline of the subject.

Description of Furnace—Of the many principles originally employed to melt steel electrically, it appears that only the system employed first by Heroult has stood the test of time. In this system the steel in the furnace forms the common conductor for the current flowing between the electrodes which enter the furnace through the roof. Fig. 1 shows a vertical section of a six ton furnace of this type. The tilting mechanism, the electrode control motor, and the switchboard control

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apparatus are often installed in separate rooms, a practice which affords protection from dirt and from the danger of heats burning through the bottom into the pit.

Current is supplied from a suitable source through the bus bars F and electrode holders G to the electrodes which are three in number, arranged in the form of a triangle. Electrodes may be either graphite or amorphous carbon. Arcs are sprung from the electrodes to the bath K, thus heating the metal both by direct conduction from the arc, and by radiation from the roof and walls. The height of the electrodes above the bath, and consequently the heat input, is controlled automatically by the winch motors H which raise and lower the electrodes.

The furnace proper consists of a cylindrical steel shell lined with refractories as indicated in the legend. The roof is detachable. The furnace is tilted about the stationary axis or trunnion E placed directly under the spout J. The tilting mechanism consists in a motor A which raises the furnace by means of the connecting rod D operated through a series of gears B. The weight of the furnace is balanced by the counterweight C.

The choice of refractories for the basic electric furnace is a very important consideration. The hearth itself must be a basic material, such as magnesite or burned dolomite, to withstand the lime slags used in the basic process. The walls and roof on the other hand need not be of basic material, but must be capable of withstanding extremely high temperatures. Silica brick is used almost exclusively for this purpose.

The hearth is either rammed in by layers, using a suitable binder such as sodium silicate, molasses, or tar, and is then burned in as a whole, or else the bottom material, often mixed with a suitable flux such as an oxide basic open hearth slag, is shoveled into the hot furnace and burned in layer by layer. This is done by the heat of electric arcs formed between the furnace electrodes and other electrodes placed across the hearth of the furnace.

Electric furnace refractories are subjected to severe service. The arches, jambs, and door brick especially have a short life, which can be lengthened by the use of water cooled doors and frames. Protection of refractories by water cooling shows up to better advantage on the larger furnaces.

The tonnage capacities in which commercial units of this type of electric furnace are built, together with the transformer capacities, are as follows:

Furnace Capacity, Tons	Transformer Capacity, kva.
1	1,000-1,200
3	2,000-3,000
6	3,000-4,000
15	4,000-7,000
25	7,500-10,000
40	12,000-13,500
100	20,000-25,000

All sizes except the 100 ton have three electrodes on the one three-phase circuit, while the 100 ton furnace has 6 electrodes with the two three-phase circuits.

The tendency is toward higher voltages during the melting down period—voltages which run as high as 250 for some furnaces. During the refining period, the voltages may be as low as 85-100. Switches are usually provided so that two or three voltages are possible at the will of the operator, and so that it is possible to have as many as 12 steps.

General Description of Process—In brief the process consists of charging into the hearth of the furnace a known weight of scrap of suitable physical and chemical character, and melting this down as quickly as possible. When the charge is melted, it is the usual practice to add a quantity of burned lime with some fluorspar or sand to act as fluxes, which together with the oxides resulting from the melting of the scrap form a highly oxidized basic slag. It is sometimes the practice to accomplish this same end by the addition of limestone to the charge. The procedure from this point depends upon whether or not it is desired to dephosphorize. If the scrap is of such a character that removal of phosphorus is not necessary, the slag is at once turned over, that is, whitened or deoxidized by the additions of crushed coke or ferrosilicon. If it is desirable to remove phosphorus, the furnace is tilted slightly and the black phosphorus-bearing slag is raked off or "pulled," a new slag of lime

fluorspar and coke or ferrosilicon made up, and the process continued as in the first case.

The description thus far applies to the so-called cold melt process. In the manufacture of tonnage steels it is sometimes the practice to duplex from a basic open hearth furnace, that is, to tap steel from the open hearth furnace where it has been dephosphorized, into the electric furnace, where it is to be given an ultimate refining under a deoxidizing slag. This is known as the hot metal process. As in the case of the cold melt process, a new slag is built up, and the process continued as in the case of the regular practice. The new slag is carefully treated with further additions of coke and other reducing agents until many of the gases and oxides resulting from the melt down, together with most of the sulphur, are eliminated from the metal. In the case of alloy steels the necessary alloy additions to bring the bath within the specified limits of composition are made during this period. Final deoxidation is accomplished in the furnace with the use of ferrosilicon and ferromanganese, the temperature properly adjusted, and the heat tapped into the ladle. In some cases final additions of aluminum or other deoxidizers are made to the ladle. The spout of the furnace is usually equipped with a skimmer, designed in such a manner as to allow the metal to flow from the furnace free from slag. The slag finally runs out after the ladle has been filled. After remaining in the ladle a sufficient length of time to allow any entrapped slag to rise to the top, the metal is poured or teemed into molds.

At intervals during the melting process, samples of the bath are taken for quick chemical analysis, so that chemical composition is known at all stages of the process, which enables the melter to make the necessary composition adjustments with carbon or ferroalloys.

With this brief outline of the process completed, the various stages will now be taken up more in detail.

Selection of Raw Material and Method of Charging (Cold Melt Process)—The bulk of the charge usually consists of selected steel scrap of such a composition that upon melting down, the bath will contain a smaller percentage of the various elements than is required in the final steel. This obviously allows for proper final adjustment with ferroalloys and carbon additions. Of equal importance is the physical condition of the charge, its thermal and electrical conductivity, and its distribution in the furnace. All of these factors have a bearing upon the economy of furnace operation. Consequently, considerable care is exercised in obtaining the proper balance between heavy and light scrap, in properly distributing these, and in distributing any other materials used in the charge, such as ore, scale and certain ferroalloys.

The Melt Down—The melting down of the charge is usually conducted at as high a voltage as possible so as to melt quickly, thus increasing furnace economy and decreasing melting losses. To accomplish this, and also to allow the later operation to be carried on at a lower voltage, most furnaces are now equipped with variable voltage transformers. For the first 15 or 20 min. of melting, the electrodes "search," that is, rise and lower as they melt through the scrap charge, and the current through the furnace fluctuates widely. This action stops, however, as soon as a pool of metal has formed under the electrode. When this pool has reached an appreciable size, the melter starts pushing the unmelted scrap toward the center of the furnace, cleaning off the banks, and gradually working all loose scrap into the bath. As soon as this is accomplished, the first slag additions are made, consisting usually of burned lime with a small quantity of fluorspar as a flux.

Refining—The refining stage in the electric melting process is of utmost importance, since it provides one of the big advantages which the electric furnace has over the open hearth. In the open hearth furnace, the process is essentially an oxidizing one because of the oxygen introduced in burning the fuel. In the electric furnace, on the other hand, the atmosphere can be controlled at will, with the result that the steel may be thoroughly deoxidized in the furnace.

The refining operation in the electric furnace may be considered as beginning with the formation of the slag, although as a matter of fact refining begins with the melting of the charge and continues over a certain period after complete melting. These operations are based largely upon reactions between the steel and the slag, which are confined to the contact surface of the two materials. They are also based upon reactions taking place within the steel itself between

certain of its original constituents and others that may have been added for the purpose, and finally upon reactions within the slag.

The outstanding feature of this slag is its basic character, meaning that its basic constituents, the most important of which is CaO , must prevail over its acid components, the chief representative of which is SiO_2 . This is necessary for the preservation of the basic furnace lining and also because the prevalence of CaO is necessary for bringing about most of the desired reactions.

These reactions aim to accomplish three distinctly different purposes, and since they would conflict with each other in several ways, they must be carried out separately and in a fixed sequence.

Removal of Oxidizable Elements, Principally Carbon and Phosphorus, But Sometimes Also Manganese and Chromium, By Oxidation—This process is carried out by the addition of an oxidizing agent to the slag, usually iron oxide. If it is intended to remove the carbon, the oxide is added in the form of scale or iron ore after the temperature of the bath has been raised as much as possible. At low temperatures it is possible to oxidize the other elements without burning out all the carbon. If phosphorus, manganese, or chromium are to be removed, it is necessary to pull the resulting black slag, since these elements are held only in a highly oxidized slag. If, as sometimes happens in the melting of alloy steels, only the carbon has to be lowered, the slag is not pulled, but the oxides of alloying elements that may have accumulated in it during the oxidation of the carbon are reduced back to the metallic state, and return to the steel.

Reduction of Oxides in the Slag—This comprises the oxides of all metals reducible by either carbon or silicon. Such oxides may have been formed unintentionally during the melting of the steel or intentionally as described above, or they may have been added for the purpose of direct reduction, or they may be continuously formed in the slag because of loosening of particles of hearth and patch material that pass through the steel and into the slag.

This deoxidation of the slag may be carried out by the use of finely divided carbonaceous material such as coal or coke, by calcium carbide, or by a metallic reducing agent such as ferrosilicon. This white refining slag usually contains enough calcium carbide so that the odor of gas is noticed when the slag is cooled in water, but it should not be too carbidic. The slag may be maintained in this condition throughout the refining period.

During the refining under the white slag, it is desirable to have the slag come in contact with the metal as much as possible to facilitate the removal of oxides and nonmetallic inclusions. Stirring the bath at intervals during this period is, therefore, helpful.

The Deoxidation of the Steel—This consists in the conversion of those oxides that are soluble in the steel, namely, FeO and CO , into insoluble ones, such as SiO_2 , Al_2O_3 , and CaO , and their separation from the metal by gravity. This separation is greatly facilitated if, instead of forming a highly infusible oxide such as SiO_2 , we attempt to form at the same time several such oxides, which through combination with each other become fusible slags. The finely divided slag particles will then coalesce into larger globules and separate themselves from the metal more easily. For this reason the final deoxidation of the steel is sometimes carried out by the addition of a so-called "double" deoxidizer, such as calcium silicide or aluminum-silicon alloys.

Desulphurization of the bath also takes place with the deoxidation of slag and steel, the sulphur combined with manganese rising to the surface of the bath, where it reacts with the CaO (lime) content of the slag to form calcium sulphide, which is absorbed and held by the white basic slag.

The presence of a deoxidizing agent in the slag during the final period is desirable. There is only one such agent that can exist in the slag, namely, calcium carbide. It must be kept in mind, however, that this carbide has practically no deoxidizing effect upon the steel. It will reduce oxides of iron, chromium, manganese, tungsten, or vanadium which have risen into the slag, but it has little effect, if any, upon oxides suspended or dissolved in the steel. It is, therefore, of no conceivable advantage to hold the steel for a great length of time under a strongly carbidic slag. Some steels require more time than others, but for high quality steels a holding period of about two hours under the white slag appears

to accomplish the desired results. No time longer than this has shown any special benefit.

Composition Adjustments—Beginning at the time the bath is first melted clean, and continuing through the refining period, occasional spoon tests are poured and sent to the laboratory for chemical analysis. Quick determinations upon these tests enable the melter to make what additions are necessary to bring the final composition of the heat within specified limits.

Additions of metallic elements are usually made in the form of ferroalloys, the exact composition of which is known. The charge should be so adjusted that the carbon content of the bath, when melted down, is lower than the final desired carbon. After slagging off, carbon additions of 10 or more points are best made by working in over the bare metal a definite amount of crushed electrode or some such carbonaceous material of known carbon content. The power may be turned off and the electrodes submerged, but the use of the crushed carbonaceous material is more certain. When only a few points of carbon are to be added, the addition of wash metal, low phosphorus pig iron, or carbon briquettes is very satisfactory.

Close and constant co-operation between the laboratory and the melting floor is necessary if narrow chemical limits are to be maintained.

Temperature Adjustment—Having brought the bath to the required chemical composition by refining operations and by the use of necessary additions, a number of spoon tests are next taken to determine its temperature and, as far as possible, its condition with regard to the progress of deoxidation. On straight carbon and some alloy steels, it is possible to determine the proper temperature by the so-called film test, which consists in taking a sample in a well slagged spoon and noting the time required for a film to freeze over the surface of the steel. With many alloy steels this is not possible and the temperature is determined by pouring the steel from a well slagged spoon in a uniform stream into a little test mold. No frozen metal should remain in the spoon and the test piece cast should have smooth sides without wrinkles. The top surface of this test piece gives also some indications as to the progress of the deoxidation, at least as far as the presence or absence of soluble oxides is concerned. It should be smooth and free from eruptions and slightly depressed in the center.

Tapping and Pouring—The heat of steel, now of proper composition and temperature and properly deoxidized or killed, is ready to tap into the ladle. This operation, as well as the final pouring, is carried on with the greatest care. The ladle, of the bottom pour type, having been properly dried, is brought up to the furnace and hung under the spout. The furnace is then slowly tilted into the tapping position, and the metal allowed to flow in a steady stream into the ladle. The exact practice employed in tapping varies in different plants. Some operators tap through a runner brick walled into the spout, thus holding back the slag until the tap is complete. Others prefer to tap slag and metal together. Temperatures are often taken with the optical pyrometer during tapping for record, and for the guidance of the melter. Usually no deoxidizers are added to the ladle, although occasionally small additions of aluminum may be made to counteract the tendency toward oxidation during the tap.

In pouring the ingots, the ladle is sometimes rested in a carriage which travels over the line of molds, but usually it is suspended directly upon the ladle crane. The principal precautions in pouring are to properly regulate the pouring rate and the character of the stream so as to pour with a minimum of splashing in the mold, thus insuring a good ingot surface. Soundness of the ingots and freedom from shrinkage cavities is insured by proper mold design, consisting in heavier walls near the bottom of the mold and in a chamber gradually widening toward the top, and by application of the so-called "hot top." This usually consists of a refractory form placed on top of the mold, acting as a reservoir of molten metal, from which the ingot is continuously fed until completely solidified.

Acid Electric Steel

By Fred Grotts*

History—The origin of acid electric steel probably begins with the development of the Heroult electric furnace in 1890. Previous to this, there was much experimental and production work done in the making of alloys in electric arc furnaces with both acid and basic linings.

Like other acid steel melting processes, acid electric practice is based on lining the furnace with silica brick, resulting in the usual acid slag reactions. The acid electric furnace was the result of an endeavor to increase the tonnage obtained from the original crucible process of making steel, which is essentially a remelting procedure, there being little or no opportunity to eliminate sulphur and phosphorus.

During the war period of 1914-1916 increased attention was given to the acid practice due to inability to obtain magnesite for the basic lining necessary in basic furnaces, the chief source of supply at that time being Austria. This helped to develop the acid method.

Application—The acid electric process, while not commonly used for making ingots, is adapted to the manufacture of steel castings for several reasons. The

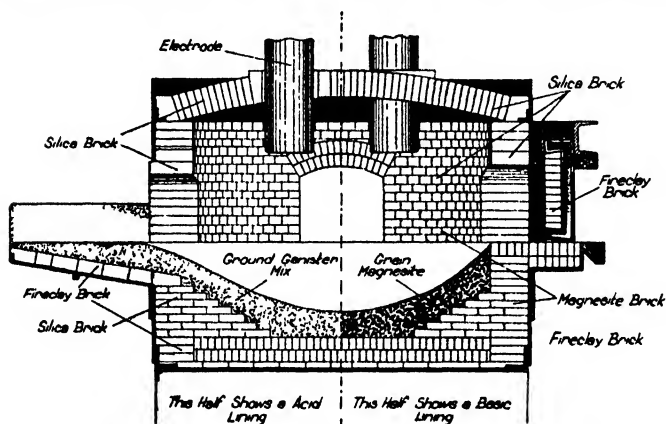


Fig. 1—Typical bricking diagram for electric furnace.

melting time is distinctly shorter than in basic practice because of the necessity in the latter practice of making such additions as are necessary to reduce the amount of sulphur and phosphorus. High temperatures are obtainable without undue reaction with the refractories which keeps such costs at a minimum. Good fluidity is also obtainable which is always desirable in producing castings. The slag, as will be described later, is also easily handled, an important item especially in lip pouring and in cases where steel with minimum slag inclusions is the objective. Many machine shops often specify acid steel for castings with machined surfaces, since it seems to be general experience that the surface of acid steel castings is superior from the standpoint of cleanness and uniformity.

Description of Furnace—The furnace consists essentially of a round steel shell lined with suitable refractories to withstand high temperatures generated by the carbon or graphite electrodes. Fig. 1 shows the method of lining in order to get the acid reaction necessary for the process. The contrast with a basic lining is also shown. The furnace is mounted on a tilting device, which is operated by electric controls. This arrangement is utilized for pouring the molten steel into ladles or other receptacles. It is recommended that the controls be placed so that the metal flow can be observed. Other electrical controls should be conveniently placed, but well protected from dirt and molten metal.

The general construction of furnaces varies considerably. In some cases the roof is detachable, in which case charging buckets carried by overhead cranes are used. These buckets are built with bottoms that open mechanically permitting the charge to be placed conveniently in the furnace.

Some furnaces have permanent tops but with side doors for charging. This arrangement permits the accurate placing of the charge, but the process is slow

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and requires more time and labor than furnaces with a removable top. Both types of furnaces have their desirable features and existing conditions sometimes call for either one or the other. Some furnaces have special tap holes which permit the holding back of slag, which procedure is usually desirable. Atmospheric control should always be kept in mind in any furnace construction.

The heat is applied to the charge by means of the arcs formed by the electrodes contacting the material, and is controlled by the height of the electrodes above the bath, or by variable voltages or taps. It is customary to use the higher voltages for melting and the lower voltage for refining. Several foundries melt down at 130-140 volts and refine at 90-110 volts; others melt down at about 200 volts and step down to about 100 volts for refining. The details of the equipment used are determined largely by the requirements of the particular practice used.

Selection of Material—The material for the charge consists of foundry return scrap, gates, heads, and risers to as much as 50 or 60% of the total, although it may be less according to the desires of the melter and the scrap available. The balance of the charge consists of plate and turnings or punchings. It is not considered good practice by some metallurgists to use too much rusty scrap on account of the possibility of gas contamination.

The acid process at present has practically no action on the sulphur and phosphorus content; therefore the materials of the charge must be as low as possible in these elements. Some operators charge the fine materials first to form a compact mass in order to minimize the tendency to form a hot pool of metal below the electrodes, while others place their plate scrap on the bottom. Too much sand on the return scrap, or too high silicon content sometimes requires higher melt down temperatures.

Charging Material—A successful procedure for a 2 ton furnace consists in scattering uniformly over the bottom about 700 lb. of plate scrap (15% approx.), 3200 lb. of returns (60% approx.), 300 lb. of flashings (5% approx.), and 1100 lb. punchings and turnings (20% approx.) for a furnace charge of 5200 lb. This charge is calculated to contain about 0.30% carbon, 0.75% manganese and 0.35% silicon. The estimated amount of iron ore, is 250 lb. which is considered sufficient to take the carbon down to below 0.10% and the silicon to about 0.05% and the manganese to about 0.10%.

The plate is charged first, then the returns, and the fines last to fill in the spaces. In some cases part of the plate may be placed on top. Some melters add ore or mill scale to the charge, while others add the oxide when a puddle has formed below the electrodes, followed by other additions as the melt proceeds.

Some observations indicate that cracked castings result from high return scrap in which case it is desirable to change to a virgin charge of purchased scrap, or else cut the returns to 15 or 20%.

Melting Operation—Melting down is carried out at high voltages, usually between 140 and 200, the exact procedure depending upon the equipment and the established practice in the particular plant. The melting operation is essentially an oxidizing procedure which gives rise to a rather violent boiling action, according to the reaction $C + FeO \rightarrow Fe + CO$ most of the iron oxide (FeO) is supplied by the ore added to the charge. The carbon is reduced rapidly from an approximate 0.30% in the charge to about 0.18% at the melt down. The boil is continued until the carbon drops to about 0.10% or less and then silicon and manganese lower still. If the original ore addition is not sufficient to lower these elements to the desired percentage, boiling should be continued by means of further oxide additions. When carbon, manganese, and silicon are "down," further oxidation is stopped, or in other words, the bath is "quieted" by an addition of low silicon pig. Some shops however prefer to let the ore boil itself out, in which case no pig is added. The slag at this stage is quite black.

In lieu of the practice just described, some melters and metallurgists prefer to "catch their heats coming down." For instance, if the charge is figured at 0.30% carbon and it is desired to finish at about 0.20% carbon, they "kill" the heat at that point with ferrosilicon or ferromanganese, rather than boil the carbon out to a low point such as 0.08% or 0.09%, necessitating later building up to the required final analysis by carbon addition.

Refining—In the boiling operation, some of the ore combines with the silicon to form silica, according to the reaction $Si + 2FeO \rightarrow SiO_2 + Fe$.

This SiO_2 is eliminated by the continued agitation of the bath, together with some manganese oxide, which is likewise formed by the addition of the ore resulting

from the reaction $\text{Mn} + \text{FeO} \rightarrow \text{MnO} + \text{Fe}$. The SiO_2 and MnO , formed are suspended in the steel temporarily, but combine quickly with the excess FeO forming iron and manganese silicates which rise into the slag. In this connection it is important to add sufficient ore or scale to almost completely oxidize the silicon, and to form fusible silicates which separate readily from the bath. The excess ore is also necessary in order to flux any sand adhering to the scrap as well as silica resulting from the erosion of the furnace lining. It might be repeated here that 250-300 lb. of ore gives a satisfactory result for a 5500 lb. charge as described.

Slag—The slag formed in the oxidizing stage of the heat is thin and rich in iron oxide, and there is a constant tendency toward equilibrium between the slag and molten metal. Some melters recommend considerable quantities of lime in melting. Such practice, however, will result in high erosion of the furnace lining with corresponding high pollution of the metal.

After the oxidizing boil has been quieted or allowed to work out, the next step is to bring the slag into condition. A satisfactory practice consists of adding about 3 shovels of dry, used molding sand and about one shovel of burned lime (CaO). Some melters use limestone (CaCO_3) which accomplishes the same result, but requires more time. Additions should be dry to avoid hydrogen pickup. The result of these additions is a noticeable thickening of the slag.

Deoxidation—The temperature is now increased and silicomanganese added. This partially cleans the steel and improves the slag, which now takes on a greenish color. Some shops practice silicon reduction from the silicate slag instead of making a silicomanganese addition. The value of this practice is somewhat controversial, but is worthy of mention since good results are reported without the use of a deoxidizer at this stage. In this connection, one of the liveliest questions is so-called "over reduction," a condition resulting from high sulphur and low oxygen content. Over reduced steel is objectionable on account of low ductility in the final casting, and can apparently be prevented by melting down with a positive boil as already described, and then avoiding the too liberal use of deoxidizers.

After the slag has been properly conditioned final additions of ferromanganese and ferrosilicon are made both for the purpose of completing deoxidation and of obtaining the desired final analysis.

Tapping the Heat—After adjusting the temperature, the heat is tapped into the ladle, preferably of the bottom pour type. The slag may or may not be held back by means of a skimmer on the furnace. Comparative tests show no difference in physical properties between the two practices. When the slag is to be held back this can easily be done by plugging the tap hole, tilting the furnace until the slag line is above the level of the hole, then removing the plug. Any aluminum addition to take care of porosity due to mold gases or impurities should be added either on the bottom of the ladle before tapping, or else placed on the end of a rod and quickly pushed through the slag to the bottom of the ladle after the tapping is complete.

There has been much discussion on the subject of aluminum in castings, and various amounts are used in different foundries. The aluminum addition seems to be governed partly by the type of molding practice; green sand practice requiring heavier additions. Many foundries who ore down their charges to low silicon, carbon and manganese contents and then deoxidize with regular deoxidizers, get good properties and sound castings in dry sand molds with the addition of 0 to 4 oz. of aluminum per ton of metal. However, in green sand practice it has been found necessary in some cases to add 2-4 lb. per ton to get good properties and solidity. It might be added that the aluminum practice just described, combined with a calcium silicide addition in the ladle has been giving reliable results for many years.

Ladle Practice—Cleanliness about the ladle is always desirable. All remaining slag from the previous heat should be removed as thoroughly as possible. A smooth lining of gannister gives good results. In lip pouring the lining material sometimes slags with the steel, as can be seen if the stream is observed from the under side. To keep back the covering slag a skimmer brick is valuable. The use of bottom pour ladles in some cases results in cleaner steel. In making small castings the metal may be transferred to bull ladles or hand shanks as desired.

Much steel is tapped at about 3100°F. into the ladle. It is good practice to hold the metal for 5 min. or more in the ladle to allow entrained slag to float out. Some pressure castings are poured at about 2850°F. or less to improve solidity. Wrinkles are likely to occur at this temperature, however, impairing the appearance of the casting. Many thin section castings are poured at 2950-3025°. Temperatures of pouring at 3000°F. or above cause a breakdown of the mold in some cases resulting in burned-in sand, and consequently rough castings.

Steel Melting in the Coreless Induction Furnace*

By Dudley Willcox and G. V. Luerssen

History—The coreless induction furnace, often referred to as the high frequency furnace, first appeared in 1917. Up to about 1922 it was used only for laboratory melting and for precious and semiprecious metals. Its larger commercial possibilities have been steadily developed since that time.

In 1925 appeared the first large installation, which was used for tonnage melting of nickel-silver and other copper alloys. Twelve hundred kw. of 480 cycle power were used to energize twelve 650 lb. furnaces, and in 1928, 26,000,000 lb. of nonferrous metals were melted with this one installation.

In 1928, the first production steel melting furnace of this type was installed, utilizing 150 kw. of 2,000 cycle power derived from a standard or salient pole type generator. Since that time the use of these furnaces has increased rapidly. Most of the furnaces have been installed by the steel industry for melting tool steel and the various stainless steel alloys. The installations have been powered with 500, 960 or 1000 cycle single phase generators in units of 60-1700 kw. capacity. Furnace sizes range from 100-16,000 lb. and are quite in contrast to the largest steel melting induction furnace built up to 1922, which held 20 lb. Since that time the use of high frequency power has been extended to several hardening applications, such as surface heating of steel shafts, and for the hardening of crankshaft bearing surfaces. Rapid localized heating of either surface or linear sections of shafts and other steel parts is a most important later development of inductive heating. In 1937 two installations were made for heating pipe for forging.

Application—The high frequency induction furnace is being used both in the making of ingots and in the steel foundry. In ingot practice it is best adapted to the melting of stainless steel and special tool steels, particularly high speed. On account of the absence of carbon pickup, and low melting loss, it provides a good tool for the production of low carbon stainless steel, since it makes possible the use of a high percentage of stainless steel scrap in the charge. In the foundry it is valuable on account of its flexibility in operation, particularly in the production of small alloy castings.

Construction of the Furnace—The coreless induction furnace is essentially an air transformer in which the primary is a coil of water cooled copper tubing and the secondary the mass of metal to be heated. The essential parts of the furnace are shown in Fig. 1. The outer shell S is made of asbestos lumber and carries the trunnions T on which the furnace pivots in tapping or pouring. Most of the shell has been cut away to show the section of the furnace. The coil C, consisting in a helix of water cooled copper tubing, is lined with a layer L of refractory material and forms a protective coating against metal leaks. This layer is continued above and below the coil against the asbestos support R, and the firebrick top and base F. The coil lining and the firebrick bottom provide a cavity into which the refractory lining of the furnace is built. This lining may take the form of a thin wall crucible or supporting shell M packed into the cavity with grain refractory G, or it may be in the form of a sintered lining described later. This lining holds the charge or bath of metal B, and is grooved out at the top on one side to form the pouring spout D.

Due to the peculiarities in construction of the furnace, in which the primary coil is fairly close to the metal bath, the selection of suitable refractories is an important consideration. The first commercial steel melting furnaces were lined with thin walled silica sleeves surrounded with silica sand or powder. Silica linings are now in use both here and in Europe and are giving excellent results. Lining life of well over 100 heats is reported, the average being about 75 heats. The general practice is to use dry ganister lined with an asbestos or steel shell which melts down with the first heat and frits the inner wall of the sand.

Many American users prefer basic linings. Magnesia grain is often used with an inner shell or thin crucible of clay-bonded magnesia. The steel shell method may be used with any lining material, but it has been found less expensive and

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more convenient in this country to use an inner shell of asbestos board made of Portland cement and asbestos fiber. This slags off on the first heat and bonds the inner layer of magnesia grain. Materials other than silica and magnesia which have been used are chromium ore, zirconium silicate, magnesite and various mixtures of magnesia and alumina.

Lining life varies greatly with the class of service. High chromium alloys tend to build up the inner wall so that it is necessary to scrape off the lining after each heat. Even then the capacity of the hearth tends to be reduced unless an occasional heat is made of some alloy such as silicon steel which cuts the lining or unless a suitable slag is used to prevent this building up. With a basic lining, and heats of stainless steel, a lining life of over 500 heats has been reported. When melting high speed steel, 100-200 heats may be expected.

Principle of Operation—In the operation of the furnace a high frequency current is passed through the primary coil or helix C (Fig. 1), inducing a much heavier secondary current in the charge, thus heating it by resistance to the desired temperature. The charge may consist either of a single lump of metal or a quantity of loose pieces such as ordinary steel scrap. Even comparatively fine turnings can be melted successfully if a moderate amount of heavier scrap is used. The current in the charge circulates in a path about its periphery in a direction parallel and opposite to that of the current in the coil. The higher the resistivity of the charge and the lower the frequency of the current applied, the greater is the radial thickness of the current path. While high frequency heating is effective over a wide range, it is practical to use about 1,000 cycles.

The heat is developed in the outer part of the charge and is quickly carried to the center by conduction, which is of course rapid through solid metals. After the charge starts to melt and a pool is formed in the bottom of the furnace a stirring effect occurs. This not only carries heat to the center of the charge by convection but accelerates melting by washing molten metal against solid metal. It also mixes thoroughly the elements in the charge, thus assuring uniformity. The flow lines in the molten bath are indicated in Fig. 2, showing that there are no "dead spots" but that every part of the bath is moved. The vigor of the stirring can be controlled by varying the power input. This is accomplished when only one furnace is attached to a high frequency generator by turning a rheostat controlling the generator voltage.

Melting Procedure—Rapid progress has been made during the past ten years in the application of this furnace to steel melting practice. The fact that development has come so fast, both from the standpoint of increase in furnace capacity and improvements in melting practice, makes it practically impossible to describe any generally used procedure at the present time. It is safe to say that in most plants using induction furnaces, the melting procedure is essentially a crucible process. Since the heat is generated entirely in the charge itself, melting is rapid and there is only a slight loss of the oxidizable elements. Furthermore, on account of rapidity of operation, preliminary bath analyses are not as a rule made. Consequently the charge is usually made up of carefully selected scrap and alloys of such aggregate composition as to produce the analysis desired in the finished steel without further additions, except possibly small amounts of ferromanganese, ferro-silicon, or other final deoxidizers.

The heavy scrap is charged first, and as much of the charge as possible is packed into the crucible. The current is turned on, and as soon as a pool of molten metal has formed in the bottom, the charge sinks and additional scrap is then introduced progressively until the entire charge has been added. Speed of melting depends upon the power input per pound of steel melted. With an input of 300 kw. it is possible to melt down a 1,000 lb. charge in 45 min.-1 hr., depending upon the character of the scrap. The additional time required to finish the heat depends upon the amount of time consumed in superheating and refining. Usually the total time is 1 hr.-1 hr. and 15 min.

In many cases no attempt is made in induction furnaces to melt under a slag cover, since, because of the convexity of the bath resulting from the stirring action, it is difficult to keep a slag blanket on the metal. Fortunately oxidation from the atmosphere is so slight that a slag does not appear necessary for protection alone. However, slags are being successfully used both during the melting down operation and for refining. The degree of convexity of the bath is governed largely by the rate of power input to the melt. A slag blanket on a one ton furnace powered with

300 kw. will be easier to maintain than on a one-half ton furnace with the same power input. The character and effectiveness of such slags is, of course, governed by whether the furnace is acid lined or basic lined. On basic lined furnaces it is reported possible to refine under a white slag similar in character to that used in arc furnace melting.

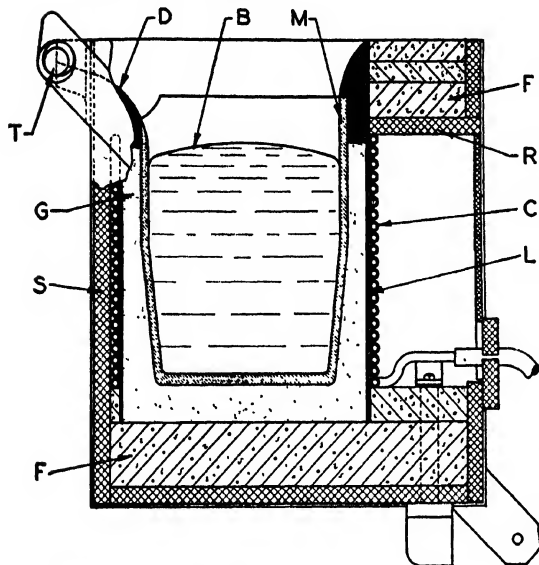


Fig. 1—Cross section drawing of induction furnace.

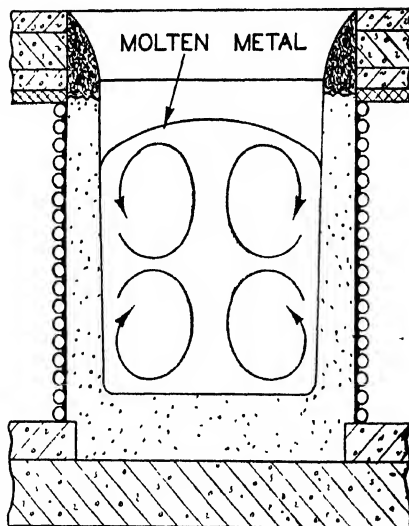


Fig. 2—Section of induction furnace showing stirring of the melt.

As soon as the charge is melted clear, and refining is completed, any further necessary additions of alloys or deoxidizers are made and the bath is superheated to the proper pouring temperature. The current is then turned off and the furnace tilted to pour the metal over the lip into the mold direct, into a funnel or pouring box placed over the mold, or into a ladle from which it is later poured into molds. In foundries making small castings it is sometimes the practice to pour into shank ladles. As soon as the heat has been poured, the furnace is scraped clean of adhering slag and immediately recharged for the next heat.

A variation of the usual melting procedure adapted to the melting of certain special alloys, consists in what is known as vacuum melting. In this process a hood is placed over the furnace and exhausted, so that melting is conducted in the absence of air or other gases.

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Crucible Process for Steel Making*

By Owen K. Parmiter

History—The production of iron and steel by a crude form of the crucible process was practiced thousands of years before the dawn of the present commercial era. The hardening properties of these ancient steels were the result of the carburizing action of the fuel, which was usually charcoal. The importance of this "carburizing" or "cementing" action was not clearly understood at first, but later it was applied to good advantage in the development of "blister steel," "shear steel" and "double shear steel." All of these steels were carburized at temperatures considerably under the melting point of the iron.

Huntsman in 1740 revolutionized the original process by melting broken pieces of the carburized blister steel in a crucible, thereby obtaining a more uniform steel. The first tool steel company was established in 1751. Mushet, early in the last century, substituted refined iron for the blister steel scrap in his crucible mix. Charcoal was added to serve as a carburizer, and the mixture was melted to form "cast steel," as it later became known. From that time on, progress in the manufacture of tool steel was relatively slow until the advent of modern analytical chemistry afforded further impetus to the production of quality steel.

Description of the Furnace and Process—The modern crucible melting furnace is of the Siemens regenerative type or some modification of it. The usual furnace has a capacity of 30 pots, each pot accommodating a little less than 100 lbs. of steel. The furnace has 5 separate melting compartments, each with an opening or "hole" which allows the operator to examine the pots during the melting process without an excessive loss of heat from the furnace. A transverse section of a crucible furnace is shown in Fig. 1 in which (A) is the melting compartment or hole. Each compartment holds 6 pots (B), and is covered with 3 brick lined covers (C), which can be pushed aside when examining the pots, or removed at the time of "pulling" or "drawing."

Regenerative gas and air chambers, (D) and (E), are arranged on either side of the melting holes. The fuel, which may be either natural or producer gas, usually the latter, is fed into the gas chambers under valve control. The necessary air for combustion is furnished by controlled stack draft. The flame resulting from the combustion of gases in the air and gas chambers is led through ports (F), three on each side of the melting compartment. Gas and air are reversed from one side of the furnace to the other every 20 min.

The bottom of the furnace proper is formed by cast iron bed plates (G). These are supported on the sides by the foundation wall of the gas chamber, and are protected from the heat by heavy tile brick (H). Over these brick, coke dust (I) is scattered to a depth of about 12 in. This

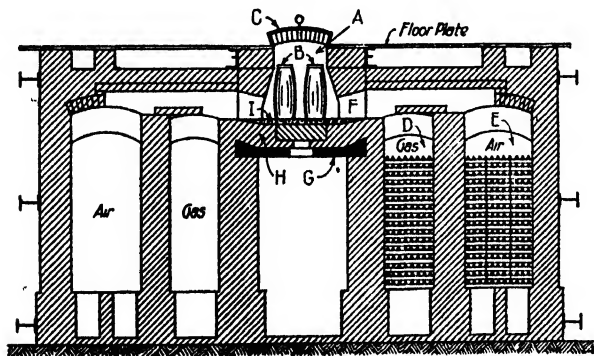


Fig. 1—Crucible furnace.

coke serves as a cushion or bed for the pots, and is of assistance in maintaining an even temperature.

The average number of heats from a crucible furnace is 6 every 24 hr., or 33 heats per week. The average recovery of steel ingots from a 30-pot furnace is about 2800 lb. per heat. The pots are made from a mixture of natural flake graphite, ball clay and silica sand, which is thoroughly wet-ground, and spun to shape. In use the pots are covered with a cap of the same material.

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The personnel of the Subcommittee on Melting was as follows: G. V. Luerssen, Chairman; G. A. Dornin, J. P. Gill, Dr. C. H. Harty, Jr., Owen K. Parmiter, and Dr. G. B. Waterhouse.

Approximately 3 hr. are required to melt a crucible charge of ordinary carbon steel. To determine when the raw materials in each pot are melted, the melter uses the "looking stick," which is a steel rod about $\frac{3}{4}$ of an in. in diameter and 6-7 ft. long. This operation is performed as rapidly as possible and the cover replaced immediately after each test. After the raw materials have melted, the charge is held for a period of "dead melting" which is about 1 hr. When the proper temperature is reached, the pots are lifted out or "pulled" by hand tongs and passed to the "teemer," who pours their contents into an ingot mold or a ladle.

While this description covers the modern furnace and melting practice used almost universally in America, a large part of the crucible steel made in Europe is still made by the original Huntsman process in coke fired furnaces.

Coke Fired Furnace—The coke fired furnace is in reality a squat shaft furnace, lined with ganister. The body of the furnace is closed by fire bars at the bottom, and has a fire brick cover at the top. Near the top of the furnace is a side flue leading to a chimney. The furnace accommodates 2 crucibles, each capable of holding about 75 lb. of steel. The crucibles or pots may be either clay or graphite, and in England the clay pot is still generally used. These pots are placed on fire brick stands resting on the fire bars and the charge introduced into the crucibles through sheet iron funnels. Lids are placed on the pots, and the whole of the inside of the furnace, still hot from the previous heat, is filled with coke.

The cover is placed in position, the dampers adjusted and the material allowed to melt, an operation which takes from $3\frac{1}{2}$ -4 hr. for the first heat and $3\frac{3}{4}$ hr. for subsequent melts. Generally, the operation of coke melting is carried out in precisely the same manner as the operation of gas melting and the success or failure of the operation depends very largely upon the skill of the operator.

Selection and Preparation of Raw Materials—The crucible method cannot remove such impurities as sulphur and phosphorus. In selecting raw materials, this fact must be given careful consideration. The base of many of the crucible mixes is puddled or charcoal iron, which must be of the best composition obtainable. The steel scrap should be clean and as nearly as possible of uniform size. The charcoal should be of the hardwood variety, in pea size pieces, with a high fixed carbon content. The ferromanganese should be of the low carbon variety, in clean, uniformly small lumps. The average crucible mix will consist approximately of the following:

Typical Crucible Furnace Mix

Carbon Steel (1.00%C.)

Ingredients	Actual Amounts, lb.	% by Weight
Puddled bar iron.....	76	80.50
Crucible steel scrap.....	17	18.00
Charcoal (75% fixed C.).....	1.25	1.25
Ferromanganese (80% Mn).....	0.25	0.25
	94.5	100.00

8 oz. of river sand per pot are sometimes used to form flux. Some use clay, black oxide of manganese, or crushed acid slag. All of these materials are accurately weighed and checked separately for each individual pot. The types of charge often vary widely with different manufacturers, some using higher percentages of tool scrap, some using foreign wrought irons, and others domestic irons.

In addition to the use of charcoal as a carburizer, wash metal, a purified iron containing 3.75% carbon, has been extensively used. As a substitute for wash metal, the Swedish white charcoal iron has had some application.

Method of Charging—The charcoal, sand, and ferromanganese are charged on the bottom of the pot, followed by all of the iron. The scrap having the lowest melting point is added near the top of the pot. Mechanical shaking devices are used to thoroughly pack the charge so that the covers will fit tightly on the crucibles.

As soon as the pots are emptied of their contents of finished steel, they are refilled with a new, cold charge, and again set in the furnace. The pots are brought up to the melting hole on small specially designed buggies. Usually a pot can be refilled 5 times, thus making the total life of the pot about 6 heats.

Melt Down and "Dead Melting" Process—The melt down should be accomplished rather quickly in a hot furnace, so that steel is melted and clear in from 2½-3 hr. After this, about 1 hr. is spent in "killing" or "dead melting." During this important operation, the furnace should be run considerably on the hot side of the proper range for the first 30 min., tapering off to the cool side for the remainder of the "firing" period. This operation serves to deoxidize and degasify the molten metal, at the same time permitting any inclusions of nonmetallic particles to come to the top and be absorbed by the slag. During this "soaking" period, the molten steel absorbs both carbon and silicon from the pot. The carbon pickup will vary from 0.05-0.15%, depending upon temperature and age of pot. When carbon pickup is undesirable, a graphite crucible with approximately ¼ in. of clay lining may be used. New graphite crucibles kill the steel more quickly than older ones because the metal absorbs more carbon and silicon from a new pot. As the pot gets older it is good practice to add more carbon and a small amount of ferrosilicon to the charge. By training and experience, the melter determines when the steel has had sufficient "fire" to rid it of nonmetallic particles and dissolved gases. Insufficient "fire" is indicated by a prolonged burst of sparks upon removal of the crucible cap. Too much "fire" produces an ingot with a "leady" structure and the resulting bar fracture appears "dry" and "dull."

Slags and Refining—The term "refining" as applied to the melting of ordinary steel usually implies the removal of undesirable impurities such as sulphur and phosphorus by oxidation or reduction in the presence of a basic flux. In crucible melting, such a process of refining is not possible because, while the pot is reducing in action, it is also of a siliceous or acid nature, which necessitates the use of an acid slag of glass or sand. Oxides and dissolved gases are removed by the reducing action of the pot. Silicon is absorbed in amounts as required and under ideal conditions to insure complete deoxidation. Carbon in the proper form is absorbed slowly from the charcoal or wash metal by the iron to produce carbides.

Composition and Temperature Adjustments—In crucible melting, all ingredients are generally added to the original charge (manganese and silicon are sometimes added to the ladle). Once the pot cover becomes sealed by the fluxing action of the container, it is seldom removed until the steel is ready to "teem" or pour. Once a mix is proven, adjustments are seldom necessary. Occasionally the carbon content may vary slightly from the desired amount, but this can be corrected by adjusting the amount of charcoal in the mix for the following heat. The "carbon throw" from the pot varies, depending upon the number of heats that have been made in the pot, but this can be regulated by proportionately increasing the amount of charcoal in the later heats. Time and temperature during the killing period directly affect the carbon "pickup," which will vary considerably unless operating conditions are held uniform by the melter.

The proper temperature for teeming depends largely upon the skill and experience of the melter. The temperature, which may be adjusted for either "hand teemed" ingots or for "ladle practice," is always higher for the ladle work. In hand teemed work, the speed of pouring can be regulated to compensate for variations in temperature.

Deoxidizers—For deoxidation, crucible steel depends upon a silicon content absorbed from the pot. If the killing time has been sufficient to give the steel the proper silicon content, and if the temperature is correct, the steel is ready for pouring. Just before this teeming operation, the slag is removed from the molten steel, thus exposing its surface to the atmosphere. Provision for this temporary exposure to oxidizing influences is made by dropping a "pill" of pure metallic aluminum into the pot. Aluminum not only prevents oxidation and keeps the steel "quiet" until it can be teemed, but it also degasifies the metal.

During recent years, the crucible furnace has been largely supplanted by the electric furnace for the melting of tool steel. The crucible process has not been abandoned entirely, however, since it still affords a method by which steel can be made efficiently in small quantities.

Metals and Ferroalloys Used in the Manufacture of Steel

By W. J. Priestley*

Introduction—Howe has aptly defined ferroalloy as "iron so rich in some element other than carbon that it is used as a vehicle for introducing that element in the manufacture of iron or steel".

A number of ferroalloys are in common use. Some of them are used for the peculiar properties they impart to steel when in solid solution with the iron or when they combine, either wholly or in part, to form a carbide; others are used for the beneficial effect they have on impurities in the steel; and still others are employed to counteract harmful oxides or gases and they may not remain in the steel after solidification, but act as fluxes or scavengers of objectionable impurities.

Standard Ferromanganese—Manganese is most generally introduced to the molten steel in the form of ferromanganese. The standard grade of ferromanganese has approximately the following analysis:

Manganese	78-82%
Iron	15-19%
Carbon	6-8%
Silicon, max.....	1.00%
Phosphorus, max.....	0.35%
Sulphur, max.....	0.05%

It is furnished in lumps up to 75 lb. each, and when made under the best conditions will not disintegrate or crumble. It is used in all grades of steel including Bessemer, open hearth, and electric for forgings, rolled products, and castings. Manganese combines readily with sulphur, forming manganese sulphide which is less harmful in steel than iron sulphide. Manganese is a fairly strong deoxidizer, and its oxide forms a fusible slag with other oxides, such as silicates, and has a beneficial scavenging effect. In effervescing steel it is desirable to keep the manganese between 0.30-0.40%, while in deoxidized steel for forgings or castings it ranges from 0.40-0.90%. Special alloy steels are made with a manganese content from 1-2% and from 12-14%. In commercial steel practice, ferromanganese is sometimes added to the ladle, resulting in a loss of from 10-20% manganese. When better steel is required, freer from slag and nonmetallic inclusions, the ferromanganese is added to the furnace. The manganese loss in this case is from 10-40%, depending upon the degree of deoxidation previously done on the bath in the furnace. Ferromanganese is often used in the furnace to increase residual manganese while the carbon is being adjusted. The melting point of the 80% ferromanganese is between 2280 and 2325°F.† Manganese improves the rolling and forging properties of steel.

Low Carbon Ferromanganese—Where manganese is desired in a low carbon steel and standard ferromanganese cannot be used on account of its high carbon content, low carbon ferromanganese is substituted. This contains 80-85% manganese, max. 1% silicon, and may be obtained with either max. 0.10 or max. 0.50% carbon. This ferroalloy is supplied in lumps up to 10 lb. each and may be added to the ladle or furnace. The latter is preferable when loss from oxidation is not too great.

Medium Carbon Ferromanganese—This alloy is used for making steel with a slightly higher carbon content than obtained from the use of low carbon ferromanganese. It is generally used for making low carbon manganese steel containing between 1.50 and 2.00% manganese. It is sometimes used in the manufacture of 13.00% manganese steel when large quantities of returned scrap with high silicon content are in the charge.

The ferroalloy is furnished in different grades depending upon the carbon and silicon analysis of the steel. Three principal grades are as follows:

	(1)	(2)	(3)
Manganese	80-85	80-85	80-85%
Carbon	1.50 max.	1.50	0.75
Silicon	1.50 max.	2.50	7.00

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†The melting temperatures given were obtained from data published by the Bureau of Mines.

It is supplied in lumps up to 75 lb. for furnace additions and in crushed form, 2½ in. dia. or smaller, for ladle additions.

Spiegeleisen or Spiegel—Spiegeleisen or spiegel is virtually a high manganese pig iron used in Bessemer and basic open hearth practice. It usually falls within the following chemical range:

Manganese	15-30%
Carbon	4.5-5%
Silicon, max.	1.00%
Sulphur	0.06%
Phosphorus	0.15%

The melting point of spiegeleisen is between 1950 and 2265°F. In Bessemer practice molten spiegel from a cupola is added to the steel, after the blow, for recarburizing and obtaining the desired manganese content. In the case of low carbon Bessemer steel, 80% ferromanganese is used in place of spiegel. Spiegel is frequently used with scrap and pig iron in an open hearth charge in order to raise the manganese content. It is more economical, however, to use a high manganese pig iron containing from 1.50-2.50% manganese.

In making effervescing steel, manganese is a good scavenger on account of its deoxidizing properties and its beneficial effect upon steel in the elimination of sulphur. Some of the troubles generally encountered in open steel are overcome by adding 0.10-0.20% manganese in the form of ferromanganese or by adding spiegel after oreing the bath. In the manufacture of deoxidized steels of forging quality, either carbon or alloy grade, or high grade castings, an addition of manganese in the form of ferromanganese or spiegel has been found highly satisfactory to clean up the bath after oreing. This is frequently accompanied by the addition of silicon in the form of silico spiegel or silicomanganese. Silico spiegel when made in the blast furnace contains approximately 4% silicon and 20% manganese. The electric furnace product contains approximately 8% silicon and 28% manganese.

Silicomanganese—For making low carbon steel in which silicon is not objectionable, silicomanganese may be used effectively for the introduction of manganese on account of its low carbon content. The use of this alloy in the refining stages of steel melting leads to the production of denser steel with fewer oxide inclusions. It is also used effectively for 13% manganese steel when large quantities of returned scrap are in the charge. Makers of low carbon-chromium and manganese steels favor it on account of the low ratio of carbon to manganese. Four different grades are available containing approximately the following percentages:

	(1)	(2)	(3)	(4)
Manganese	65-70	65-70	65-70	65-70%
Silicon	20-25	16-20	14-18	12-14%
Carbon	Max. 1.00	Max. 2.00	Max. 2.5	Max. 3%

This is furnished in lumps up to 75 lb. each or in crushed form.

Ferrosilicon Alloys—Ferrosilicon is supplied in a number of grades depending upon its purpose. Silicon has a great solvent power for gases and a stronger affinity for oxygen than manganese. It is, therefore, used for its quieting effect upon wild or oxidized steel. It may be used in effervescing steel in small amounts to clean up the bath. Larger percentages of silicon are used in deoxidized steel for high grade forgings, rolled products, and castings. The range of silicon content in the various grades of steel is approximately as follows: Effervescing steel, sheets and boiler tubes, below 0.02; semikilled steel, under 0.10; forging quality steel, 0.10-0.25; steel castings, 0.30-0.80; sheet steel for magnetic circuits in alternating fields, 1.0-5.0%.

15% Ferrosilicon—As a deoxidizer and scavenger for furnace use, silicon may be procured in a ferroalloy analyzing: Silicon, 14-16; carbon, max. 1; phosphorus, max. 0.05%. This is furnished in pigs up to 100 lb. each. The melting point of 15% ferrosilicon is about 2180°F. When used as a furnace deoxidizer, a large portion of the silicon added is not recovered but rises out of the metal as a silicate. In forging steels or alloy steels, it is useful as a preliminary scavenger for maintaining uniform analysis and higher recovery of alloying elements such as manganese and chromium when added later.

50% Ferrosilicon—The largest tonnage of silicon is consumed in the form of 50% ferrosilicon containing approximately 47-52% silicon and 48% iron. Its melting point is about 2170°F. This alloy is furnished in lumps up to 50 lb., and when made

under the best manufacturing conditions will not disintegrate or crumble when exposed to the air. In acid open hearth and acid electric furnace practice this alloy may be added to the ladle or to the furnace. The silicon loss in each instance is approximately 5%. In basic open hearth practice best results are obtained by adding it to the ladle in crushed form. The silicon loss varies from 10-30%, depending upon the degree of previous deoxidation of the bath and the amount added.

75% Ferrosilicon—For making steel of higher silicon content, some melters prefer a 75% ferrosilicon alloy. The approximate analysis is: Silicon, 75-79; iron, 20%. This is furnished in lumps up to 50 lb. each or in crushed form. The melting point is about 2150°F. The addition of concentrated grades of ferrosilicon to molten steel generates heat that is particularly apparent in the production of steels with more than 2% silicon and steps should be taken to allow for this change.

90% Ferrosilicon—In cases where ladle additions of cold ferroalloys must be large in order to give a high silicon content in the steel, it is desirable to use 90% ferrosilicon. This alloy contains approximately: Silicon, 90-94; iron, 4.50%. This is furnished in lumps up to 35 lb. each or in crushed form. The melting point is about 2150°F.

Ferrochromium—The amount of chromium added to steel for structural purposes varies from 0.50-6.00%. When chromium is added in amounts between 11.00-14.00% with the carbon above 0.20%, the steel resists corrosion after being heat treated. However, if the carbon is below 0.10% and the chromium 13.00% or higher, the steel resists corrosion and oxidation in both the heat treated and untreated conditions. For resistance to more severe corrosion and oxidation at higher temperatures, chromium is added in amounts up to 30%.

For steel containing medium carbon and chromium, a high carbon ferrochromium of approximately the following analysis is used:

Chromium	60-72%
Carbon	4- 8%
Silicon	2- 3%

This alloy is furnished in lumps up to 75 lb. or in crushed form. On account of its slow melting to a liquid state, ferrochromium should be added to the furnace in all cases and never to the ladle. Its melting point has been reported from 2200-2370°F. In the basic electric, acid electric, and acid open hearth processes, the chromium loss is approximately 5%. With the basic open hearth process approximately 10% chromium is lost.

Low Carbon Ferrochromium—For making low carbon steel, where high carbon ferrochromium would be unsuitable, a low carbon ferrochromium is used. This is supplied in a number of different carbon grades to meet the steel maker's special requirements.

These grades range from a maximum of 0.06 to a maximum of 2.00% carbon, chromium 60-72%, and with a maximum of 1.00% silicon. The melting point ranges from 2300-2480°F. This alloy is furnished in lumps up to 75 lb. or in crushed form.

High Nitrogen Ferrochromium—High nitrogen ferrochromium is available in both the high carbon and low carbon grades. The chromium content of these high nitrogen ferrochromiums varies from approximately 60-72% and the nitrogen content from 0.60-0.70%.

Ferromolybdenum—In engineering steels the amount of molybdenum rarely exceeds 1% and is nearly always used in combination with nickel, chromium, vanadium, or manganese. In most cases the amount is between 0.15 and 0.50%. In the molybdenum high speed steels, the molybdenum may be as high as 10%, replacing part of the tungsten.

Ferromolybdenum has approximately the following analysis:

Molybdenum	55-65%
Sulphur	max. 0.25%
Silicon	max. 1.50%

Ferromolybdenum is furnished in two grades containing maximum 0.50 and maximum 2.00% carbon. It is generally used in crushed form, 1 in. and down. Ferromolybdenum is not ordinarily added to steel in the ladle, but is usually added in the furnace. Since it does not oxidize under steel making conditions, it may be charged into the furnace any time up to one half hour before tapping. Molybdenum steel scrap should be kept separate from other steel scrap on account of its valuable

molybdenum content which may be recovered in remelting. The recovery of molybdenum is in excess of 90%. The approximate melting point is 2965°F.

Calcium Molybdate—Calcium molybdate contains about 40% molybdenum, 25% calcium oxide, and no carbon. This product is suitable for steel made in the open hearth and electric furnace. The molybdenum recovery in this form is equal to that obtained from ferromolybdenum.

Calcium molybdate is not made as a final addition like most ferroalloys, but is added either with the charge or at any time during the progress of the heat, preferably after the heat is melted. In a basic electric furnace it may be added immediately after slagging off with good results.

Calcium-Molybdenum-Silicate—Calcium-molybdenum-silicate contains about 40% molybdenum, 23% calcium, and 16% silica. As this product is practically neutral in its action, it is suitable for additions to either acid or basic furnaces.

Due to its heavy, lumpy consistency, it can be added at any time during the heat from the melt down up to within a few minutes of the tapping. When thus added it gives a uniformly high recovery and uniform distribution.

Ferrovandium—The amount of vanadium added to engineering steels is generally 0.10-0.25%. In high speed steel, the proportion ranges between 1 and 5%. Alloy tool steels other than high speed contain from 0.20-1.00%. It is added to steel in the form of ferrovandium, the approximate analysis of which is as follows:

Vanadium	35-40%
Silicon	1.50-8%
Carbon	0.20-3%

It may be obtained in lumps up to 10 lb. or in crushed form. Vanadium oxidizes readily so in open hearth practice it is usually added to the ladle. Its melting point is between 2600 and 2700°F. The vanadium loss in this process is approximately 10%. In basic electric practice, it is generally added to the furnace with a vanadium loss of approximately 4%.

Titanium—Several forms of titanium alloys are used in steel making. The high carbon grade is known as ferro carbon-titanium and contains about 17% titanium, 7.50% carbon, 2.50% silicon and 1.00% aluminum. It is used as a deoxidizer and scavenger, leaving only barely appreciable amounts of titanium in the solid steel. In low carbon effervescing sheet steel, ferro carbon-titanium is used to prevent blisters and other surface imperfections. In medium or high carbon killed steels ferro carbon-titanium is used for deoxidation and to promote freedom from segregation. Titanium reacts with nitrogen in the steel and forms minute pink crystals of titanium nitride. Several low carbon grades in use are known as low carbon ferrotitanium. One grade is made by the aluminothermic process and contains about 25% titanium, 6.00% aluminum; another grade is made in the electric furnace and contains 15-20% each of titanium and silicon with less than 1.00% aluminum and less than 0.50% carbon. In these forms the titanium acts as a deoxidizer and scavenger and also as an alloying element. For austenitic stainless steels some prefer a grade containing 20-25% titanium while others find an alloy with 40-45% titanium satisfactory. In both grades it is desirable to keep the silicon and aluminum as low as possible and the carbon is usually specified under 0.10%.

Ferrotungsten—The principal use of tungsten is the manufacture of high speed steels which contain a wide range of tungsten, from 14-20%. It is also the principal constituent of permanent magnet steel, and hack saw steel, generally containing from 1-5% tungsten. Tungsten steel is made either in the crucible or electric furnace.

Ferrotungsten has approximately the following analysis:

Tungsten	78-83%
Silicon, max.	0.75%
Carbon, max.	1.00%

Ferrotungsten has a melting point between 3275 and 3450°F. and should, therefore, always be added to the furnace or crucible. The size commonly used is 1 in. and down. On account of its melting point being lower than tungsten powder, some steel makers prefer ferrotungsten.

Nickel—Nickel is used in engineering steels from 2-5% and in higher percentages for heat resisting and acid resisting parts. Nickel is added to the furnace in a metallic form containing about 99% pure nickel. It is not removed from steel by

oxidation at steel making temperatures, therefore, nickel scrap should be kept separate from other steel scrap on account of its recovery value. As there is no furnace loss, the nickel may be charged into the furnace any time during the progress of the heat.

For steel making the following two grades of nickel are available:

	Electrolytic Cathode Nickel, %	Remelted Electrolytic Nickel, %
Nickel (plus cobalt).....	99.95	99.60
Melt point, °F.....	2650	2600

Ferrocolumbium—Columbium has a strong affinity for carbon and forms a stable columbium carbide constituent. It is used for modifying the air hardening characteristics in plain chromium steels of the corrosion resisting grades. Since columbium inhibits intergranular corrosion in austenitic 18-8 stainless steel, it is used in this grade of steel requiring welding or long time holding up to 1500°F. Columbium also increases oxidation resistance in chromium steels at elevated temperatures.

The amount of columbium added to steel varies from five to ten times the carbon content depending upon the service in which the steel is used. It is available as a ferrocolumbium alloy containing 50-60% columbium. When added to the steel after deoxidation, and 12-15 min. before tapping, 80% of the alloy will be recovered.

Zirconium—Zirconium is used as a deoxidizer and scavenger of steel in amounts between 0.05 and 0.10%. It acts on the oxygen and nitrogen in the steel, tending to eliminate them as well as nonmetallic inclusions. An addition of 0.08-0.10% will usually result in a fine grain steel. In amounts of 0.10-0.15%, it forms zirconium nitride. When present in steel above 0.15%, it combines with sulphur, forming zirconium sulphide. This prevents tearing in rolling and produces a better surface on high sulphur steel. For steel of high silicon content, the 12-15% zirconium alloy is used, the approximate analysis of which is as follows:

Zirconium	12-15%
Silicon	39-43%
Iron	40-55%

For steel of low silicon content, the 35-40% zirconium alloy of the following analysis is used:

Zirconium	35-40%
Silicon	47-52%
Iron	6-10%

Zirconium is frequently added to steel in the form of a ternary alloy containing 20-24% zirconium, 10-12% manganese, and 58-62% silicon. It may be most effectively added to steel in the ladle, where it has a strong deoxidizing action and forms a fusible slag which tends to rise out of the metal. For the control of grain size, an alloy containing 45% silicon, 7% aluminum, 7% vanadium, and 7% zirconium is used as a ladle addition.

Cobalt—Cobalt resembles nickel in appearance and properties. It has been added successfully to high speed steel in amounts from 1-12% for the purpose of obtaining a cutting tool which would hold a sharp edge. It is used for making magnet steels containing about 35% cobalt. An alloy containing about 19.5% cobalt is used as a substitute for platinum for certain uses. It is also used for a new electrical resistance alloy for high temperatures. Pure cobalt has a melting point of 2631°F. It is usually added in the form of cobalt metal of about 97-98% pure, or in the form of ferrocobalt containing 90-94% cobalt, balance iron.

One of the chief uses of cobalt, in this country, is in the manufacture of Stellite. It is also often used as an alloy in making permanent magnet steel.

Aluminum—Because it is an extremely active deoxidizer and degasifier, aluminum is used in substantially all steel making processes. It is used as a mould addition to quiet wild metal. It is also used in the ladle for obtaining a fine grain size and to prevent pin holes in steel castings. Aluminum is a constituent of the majority of nitriding steels. Aluminum is available in several forms such as shot, sticks and small ingots. The amount used depends on the steel making practice and the use for which the steel is intended. The melting point of aluminum is approximately 1218°F.

Copper—When used alone as an alloying element, the range of copper is between 0.20 and 0.50%. The rust resisting properties of steel are claimed to be increased by raising the copper content to 0.40% along with 0.05% molybdenum.

Since copper does not oxidize in steel it cannot be removed from scrap once it is present as an alloy. This results in small percentages of this element remaining in all steel made from copper bearing scrap.

Copper has a low melting point (approximately 1981°F.) and alloys readily with steel up to about 1%. Additions are made to the furnace in the form of pure copper pigs. Copper is harmful to some grades of steel, particularly hardened tool steels containing over 0.60% carbon. The detrimental effect of copper is directly proportional to the carbon. Some improvement in the poor rolling properties of high copper steel may be obtained by increasing the manganese or by the addition of half as much nickel as copper.

Calcium-Silicon—Calcium is exceedingly active chemically and combines readily with oxygen and other gases and reduces nearly all metallic oxides on heating. Calcium-silicon is used as a deoxidizer, degasifier and reducing agent in steel making. Both calcium and silicon are active deoxidizers and form a low melting point slag which readily frees itself from the metal. Calcium-silicon also improves the fluidity of the steel. It is usually used in crushed form, 2 in. and down, and is added in the ladle in open hearth steel making as a final deoxidizer. From 2-6 lb. are used per ton of steel. In electric furnace melting it is used preferably in the furnace where it quickly forms a fluid reducing slag.

The range of elements in this alloy is as follows:

Calcium	28-35%
Silicon	60-65%
Iron	3- 6%

Its melting point is between 1850-2100 degrees F.

Calcium-Manganese-Silicon—This is a ternary deoxidizer containing three active elements, the combination of which forms a scavenger for oxides, gases and nonmetallic impurities in steel. When used as a final alloy addition to steel it produces a clean, coarse grained structure with deep hardening properties. It is also used to deoxidize stainless steel, high speed tool steel. The alloy contains 16-20% calcium, 14-18% manganese, 55-60% silicon. The alloy addition is generally based upon a silicon content required in the steel.

Its melting point is between 1800-2000°F.

Aluminum as a Deoxidizer

By John Chipman*

Aluminum is used in the manufacture of many widely different grades of steel. Aside from its rather limited use as an alloying element, its main purpose is to reduce the content of ferrous oxide in the liquid steel. When this reduction amounts to substantially complete elimination, the resultant steel is found to be fine grained, as judged by the McQuaid-Ehn test.

Of the elements commonly used as deoxidizers aluminum is the most potent, and affords the most nearly complete removal of dissolved ferrous oxide. The reaction in its simplest form is written as follows:

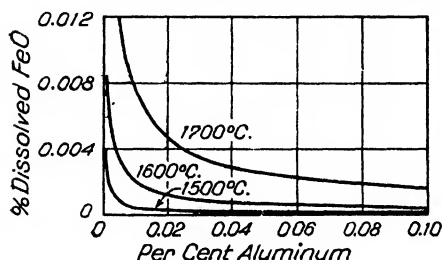


Fig. 1—Deoxidation diagram for aluminum in steel.

cleanliness. The amount used ranges from a few ounces to as much as four lb. per ton, depending upon the grade of steel, the slag, other deoxidizers used, and the grain size desired.

The completeness with which aluminum removes dissolved FeO from the steel bath is shown in Fig. 1, which was obtained from the calculated equilibrium constant of the reaction. Fig. 1 shows, for example, that in a bath at 2910°F., if enough aluminum is added to react with the other oxides present, and to leave a residual, 0.01% metallic aluminum dissolved in the steel, the content of dissolved FeO will be reduced to 0.002%. Similarly, if the bath temperature is 3090°F., and the residual metallic aluminum 0.02%, the dissolved FeO will be less than 0.005%. It should be emphasized that these figures are based upon calculated, rather than experimental, values of the equilibrium constant. In view of the limitations of present experimental methods when applied to small amounts of aluminum and oxygen at high temperatures, the calculations are probably more dependable than direct determinations.

Aluminum is added to rimming and semikilled steels to diminish the content of active FeO and to control the action in the molds. The amount used in rimming steels will range from 0 to 0.4 lb. per ton in the ladle (for semikilled 0-0.7), and up to half this amount in the molds. The amount will vary with the carbon and manganese content of the steel, the composition of the slag, the size of the heat, and the size of the mold. In general the rimming action contributes to the removal of the products of deoxidation and the use of aluminum in the molds does not necessarily lead to the presence of nonmetallic inclusions. The amount of aluminum added is never sufficient to react with more than a small fraction of the ferrous oxide present. Reference to the deoxidation diagram shows that in this case the residual metallic aluminum in the steel is practically nil.

When an excess of aluminum is employed, the inclusions formed in the reaction consist of Al_2O_3 , more or less contaminated by FeO and other oxides. When a deficiency of aluminum is used, the resultant inclusions are mainly ferrous aluminate, whose exact composition is unknown and probably variable.

In killed steel the aluminum is generally added to the ladle, although in certain grades of electric furnace steel some melters add it in the furnace. Its use in the molds in killed grades is usually prohibited by consideration of

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The Use of Aluminum for the Control of Grain Size in Commercial Steels

By H. W. McQuaid*

The importance of the control of grain size in commercial steels has become so well recognized in recent years that the method used in obtaining this control is of general interest to everyone responsible for the treating and application of commercial steel. "Grain size" as used here refers to the austenite grain as indicated by the McQuaid-Ehn carburizing test or other suitable measure of austenitic grain size and is rated usually according to the chart of the A.S.T.M.¹ (See p. 750 and 754.) Practically every heat of carbon and alloy steel specified in this country for heat treated parts is made according to a certain melting practice designed to provide properties in the steel which will make it most suitable for the part in which it is to be used. The McQuaid-Ehn grain size is used as an indicator of the characteristics of the particular steel in its response to normalizing, heat treatment, and other processing, and has become in many cases of equal importance to the chemical specification in the results obtained in the commercial heat treatment of steels.

The most important single factor in the control of grain size is aluminum, so that this element which at one time was considered detrimental as an addition to quality steel, has become a familiar sight on the melting furnace floor. It has been found by experience that additions of aluminum from a few ounces up to as high as 4 lb. per ton result in variation in grain size and characteristic properties according to the condition of the steel to which it is added.

It might be well at this point to note that the making of steel to a definite grain size range is only commercially possible when the specifications cover either a coarse grained type or a fine grained type. Although it is possible, and specifications require it at times, that steel be made which will show according to the McQuaid-Ehn test an intermediate grain size range, it should be remembered that steel of this type requires very careful control of every factor and is not usually considered "commercial."

One of the first published evidences of the effect of aluminum on grain size is shown in Fig. 1. There is no doubt but what prior to this time aluminum was added to improve certain properties of steel, but it was not until a little more than 10

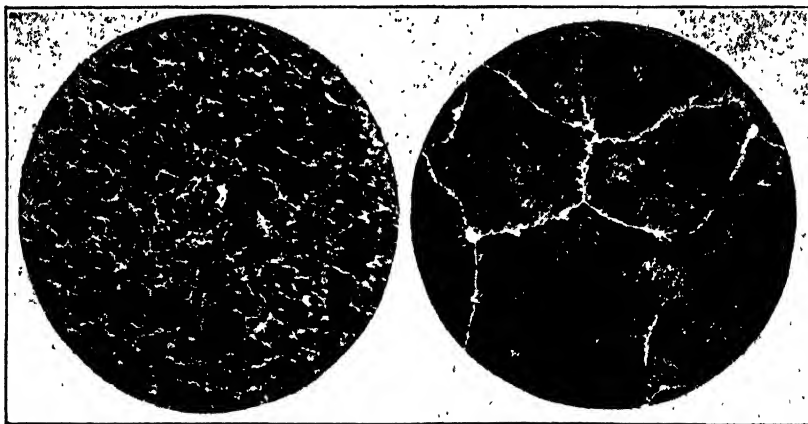


Fig. 1—Fine grain obtained by aluminum deoxidation as contrasted with the coarse grain of manganese deoxidation. (Left) Hypereutectoid specimen from ingot deoxidized with aluminum. (Right) Hypereutectoid specimen deoxidized with ferromanganese. $\times 200$.

years ago that active work was done in connecting the aluminum addition with grain size specifications. As soon as the first grain size chart appeared in 1924 and some steel users insisted on obtaining steel of a definite grain size, it was found

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necessary to develop a melting technique which would make it possible to meet these specifications commercially (Fig. 1).

It was known that in the plain carbon grade particularly, that fine grained steel could be produced without the use of aluminum, depending entirely on the presence of excess FeO, but that when so produced the quality of the steel was decidedly inferior to that desired and recourse was had to aluminum. It was soon found that if the steel were to be produced to meet a given grain size specification by the use of aluminum, that it was necessary to give much greater thought to the deoxidation of the steel prior to the aluminum addition; and thus, a great deal of study was required of open hearth deoxidation with a view to more completely controlling the variables of oxidation.

Aluminum, being one of the most active deoxidizers of which we know, must be carefully added to a bath of liquid steel if the losses due to oxidation are to be within reasonable limits and also if the aluminum is to be effective in its role as a grain growth control agent.

It is of course evident because of the great affinity aluminum has for oxygen, that the addition of stick aluminum to the ladle will result in a high loss of aluminum in the form of oxidation at the surface of the steel. For this reason a special effort should be made to keep the aluminum as added as completely submerged as possible to prevent not only the high loss of aluminum in the slag but also the presence of large masses of aluminum oxide in the steel itself.

It has been found that to be effective, aluminum must be added in connection with silicon. At the present time we do not know why silicon plays such an important part in connection with aluminum, but it is known that in the absence of silicon, aluminum is much less effective. For this reason deoxidation with silicon is a necessary requirement of all heats in which aluminum is to be used to control grain size.

The three most important factors which govern the effectiveness of the aluminum addition in controlling grain size are the state of deoxidation of the bath, the temperature of the bath, and the time of the aluminum addition in relation to the solidification of the ingot. One of the difficult problems of determining the proper addition of aluminum to an open hearth heat to make fine grain steel was the control of the deoxidation and temperature prior to the addition of aluminum.

In the electric furnace, melting under a so-called carbide slag, the FeO in the slag and in the bath itself is relatively low so less aluminum is required than when steel is made under a basic open hearth slag.

In order to arrive at a satisfactory basis for the addition of aluminum to open hearth steel, the charge must be carefully regulated as well as the rate at which the oxidation of the carbon takes place, so that when the time comes for the final shaping up, we can arrive at a bath which is under control not only as far as carbon is concerned, but which has also reached a stage of semiequilibrium as far as the slag and the oxide in the steel is concerned. Special attention is paid to the rate at which the carbon is oxidized and also to the amount of iron oxide in the finishing slag so that it can be assumed that when the deoxidation additions are made of silicon and manganese, that the final steel in the ladle will contain a certain iron oxide content. Knowing the oxide content and the temperature, the aluminum can be added in the open hearth ladle to produce the fine grain steel if required. The addition of the aluminum in the ladle is generally made by the use of stick aluminum which should be carefully added to insure lower oxidation losses. Aluminum alloys such as silicon-aluminum-manganese, iron-aluminum-silicon, and iron-aluminum alloys have all been used to obtain a better control of the aluminum addition, although the common practice is still to use stick aluminum which is thrown into the ladle by hand as the ladle is being filled.

In the basic open hearth furnace, the usual addition required to meet a fine grained specification varies from 12 oz. to 2 lb. per ton. The usual minimum addition for a fine grained steel is approximately 1 lb. per ton, although where the maximum effect is required additions up to 32 oz. are not uncommon. It has been observed that as the addition of aluminum increases above 32 oz. per ton that there is no further increase in the grain refining effect and, in fact, if the aluminum addition is greatly increased above this point that there is a decided tendency to produce coarse grained steels. The aluminum cannot be considered to have a straight line

effect on the grain refinement, but reaches a maximum at approximately 32 oz. per ton and from then on decreases rapidly in its grain refining effect. It has been found that the manner of the addition of the aluminum has an important effect on the amount required and that where the aluminum is so added that it melts below the surface of the steel bath much less aluminum is actually required. This is an important factor in determining the amount of aluminum required and it is quite evident that much lower amounts of aluminum are necessary than is the case where stick aluminum is added to the open ladle.

Table I

Effect of Aluminum Addition on Grain Size in Commercial Heats—(Epstein, Nead, and Washburn)

Ladle C	Analysis, %—		Furnace Additions	Aluminum— Additions, oz. per Ton		Grain Size— Medium, Large, or Small		
	Mn	Si		Ladle	Mold	2-3	Mixed	5-7
0.19	0.44	0.10	Si-Mn	12	...	•		
0.19	0.39	0.10	Spiegel + Fe-Si	..	2.6		•	
0.22	0.47	0.12	Spiegel + Fe-Si	16	...			•
0.37	0.71	0.07	Spiegel + Fe-Si	16	...	•		
0.43	0.55	0.07	Spiegel + Fe-Si	16	...	•		
0.38	0.55	0.13	Spiegel + Fe-Si	16	...	•		
0.35	0.79	0.19	Spiegel + Fe-Si	16	...			•
0.38	0.67	0.19	Spiegel + Fe-Si	16	..			•
0.55	0.55	0.16	Spiegel + Fe-Si	12	½	•		
0.59	0.69	0.18	Spiegel + Fe-Si	16	...			•
0.79	0.74	0.20	.....	..	...	•
0.78	0.68	0.15	.....	16	...			•

In the basic electric furnace, the additions of aluminum required to obtain a fine grained type are usually somewhat less than in the open hearth depending upon the character of the charge and the type of slag used. Due to the variation in furnace condition and the degree of deoxidation, it is impossible to give any hard and fast rule as to the exact amount of aluminum which must be added to produce a fine grained heat.

The literature does not contain many references to the specific use of aluminum in steel making practice. Epstein, Nead, and Washburn,² as well as Epstein and Rawdon,³ and Herty⁴ and his associates, have discussed the specific effect of given amounts of aluminum added to commercial heats, and the reader is referred to these papers for examples of the effect of specific additions of aluminum in the ladle and also in the mold on the grain size of the finished steel. The reaction of deoxidation with aluminum is discussed in reference 4.

With the exception of certain heats of structural and rimmed steel, aluminum is added to practically every heat of steel to some extent, except where the specifications require the coarsest possible grain size and even in such cases special attention must be given to the slag condition, and rate of carbon elimination.

Aluminum is an extremely important addition to carbon steels. It is also of almost equal importance in alloy steels and particularly in steels which are used for parts where minimum distortion, due to quenching stresses, is important, and in parts which are subjected to suddenly applied loads. The aluminum addition is of the greatest importance in gear steels which do not contain vanadium and practically every specification for these steels today requires the use of a carefully regulated addition of aluminum.

How the aluminum acts to cause this variation in properties is, at the present time, a more or less controversial subject, there being apparently two schools of thought. One of them attributes the relation between the grain size and the aluminum addition to a dispersion of alumina particles of submicroscopic but critical size, which act as nuclei of crystallization and interfere with the normal grain growth.

The other school of thought believes that the alumina theory of grain size con-

trol is not satisfactory and that the aluminum effect on grain size is due to its effect on the solubility of constituents such as carbides and nitrides.

According to Bain,⁵ the aluminum acts indirectly by forming submicroscopic, uniformly dispensed particles of alumina which act as obstructing agents in restricting grain growth. The hardenability varies with the grain size so that the aluminum in the oxidized form, by restricting grain growth, tends to indirectly reduce the hardenability of the steel to which it is added.

On the other hand, there are some metallurgists who do not believe that the alumina can in itself be the final answer to the effect of aluminum in restricting grain growth. Whether the aluminum acts directly or indirectly to cause the variation in characteristics is discussed by the writer in the Tenth Annual Campbell Memorial Lecture, and a hypothesis is offered suggesting metallic aluminum in solution and its effect on carbide coalescence as a cause of grain growth inhibition and pearlite divorce.

Schane⁶ expresses himself as believing that the restriction of grain growth in the fine grain steel cannot be satisfactorily explained by the oxide dispersion theory.

Scott⁷ shows that steel made from highly purified iron and known to be extremely low in oxygen content is fine grained after an aluminum addition, whereas other alloys made from purified iron without the addition of aluminum developed relatively a much coarser structure on heating slightly above the A_c .

In a paper on grain size and quality of steel by Ohman,⁸ together with comments by other prominent Swedish metallurgists, there is some discussion as to the reaction of aluminum and a considerable difference of opinion prevails as to the manner in which aluminum acts to promote grain growth restriction.

The common practice in this country is to add aluminum in the ladle, whereas, according to Ohman, the Swedish practice is to add it in the mold. Epstein shows that the mold addition of aluminum is apparently more effective in producing fine grain than the ladle addition, and theoretically the mold addition should be the most economical. Experience has shown that apparently more satisfactory results are obtained in large basic open hearth heats by a ladle addition.

While the aluminum addition is an important part of making carbon and alloy steel, there is still much work to be done to improve the results which are obtained. Considerable study is being given to the timing of the addition and to the method of making the addition, and there is no doubt but that this will result in a more highly developed control of open hearth heats.

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Ingot and Pouring Practice

By G. A. Dornin*

General—After the furnace operations are complete the next step in producing a heat of steel is to get the metal into a solid homogeneous casting. In foundry practice, the casting will be of approximately finished size and shape. In ingot practice, the casting will take the form of a chilled ingot, which is to be rolled or forged into the final form. Regardless of the steel making process used, the procedure after the metal leaves the furnace consists of two distinct steps, first, tapping the heat into a container, called a *ladle*, and second, pouring from the ladle into molds having the size and shape of the ingot desired.¹

Ladle Practice—The function of the ladle is to act as a container or reservoir for the molten steel after it leaves the furnace. From the ladle the molten steel is poured into the mold. As steel practices and furnace capacities differ greatly, so also do the character and size of ladles differ to fit the various operating conditions. Steel ladles vary in size from approximately 100 lb., typified by the small hand-shank ladles used in foundries, to 100 tons, the usual size employed in large open hearth plants. In type, they fall under two general classes: *lip pour*, and *bottom pour*.

Lip Pour Ladles—This ladle is used in steel foundries, and in some Bessemer plants, and as the name signifies, it is constructed so that the metal is poured over the lip by tilting the ladle. It usually consists in a bucket-shaped shell of steel plate, having trunnions on the sides for engagement with a crane bail. The shell is lined with a layer of special refractory fire brick, or a mortar of ganister, clay, or sometimes magnesia. In practice the metal is tapped from the furnace, the slag being allowed to run on top to act as a cover. In pouring into molds, the ladle is tilted on the trunnions, usually by means of a worm and gear, the metal running over the lip, while the slag is held back. Small shank ladles often used in the foundry are simply steel pots lined with foundry sand or clay and properly dried. A modification of the lip pour ladle is the so-called tea pot ladle, in which an independent spout or tube is built down through the lining so as to connect at the bottom. This allows lip pouring in such a way as to draw the metal from the bottom of the ladle, thus avoiding contamination by the slag. This type of ladle is convenient in foundries handling basic steel, and particularly high manganese steel, which is notably corrosive on stoppers and nozzles.

Bottom Pour Ladle—This ladle has a steel shell of much the same shape as the lip pour ladle. It has trunnions for either hanging on a crane by means of a bail or for holding in a carriage or a buggy. Bottom pour ladles are usually lined with brick, sometimes used bare, and sometimes with a plaster of fire clay over the surface. The shell has a hole in the bottom close to the rim in which is inserted a refractory *nozzle* made of clay, graphite-clay or magnesia. Into this nozzle fits a *stopper* or *plug* made of a graphite-clay mixture. This stopper is held on a steel stopper rod which is protected by clay sleeves and extends vertically through the bath of metal. The top end of the rod protruding above the top of the ladle is fastened to a goose-neck extending over the side of the ladle which is raised and lowered by a lever. By this arrangement the flow of metal through the nozzle can be controlled. The sizes and types of nozzles and stoppers vary to suit specific purposes. In all cases the primary purpose is to deliver a smooth stream at the proper rate and temperature with the minimum amount of erosion of the stopper parts. Fig. 1 shows the section of a bottom pour ladle.

Operation—All ladles must be carefully dried before tapping the metal and in some cases, particularly in the smaller sized ladles, not only dried, but heated to a good red heat. In the case of the bottom pour ladle, the stopper is set when the ladle is cold, then unlocked from the rigging, and the ladle and stopper heated separately. When the steel is ready to tap, the stopper is keyed into the ladle, pulled tight into the nozzle, and held there with a set screw on the saddle of the

*Prepared for the Subcommittee on Melting by G. A. Dornin, Baltimore. The membership of the subcommittee was as follows: G. V. Luerssen, Chairman; G. A. Dornin, J. P. Gill, Dr. C. H. Hetty, Jr., O. K. Parmiter, and Dr. G. B. Waterhouse.

¹There are two possible exceptions, namely, in the crucible process, where it is sometimes customary to pour direct from the pot into the mold, by what is known as single practice, and in the high frequency induction furnace, where it is sometimes the practice to pour from the furnace direct into the mold.

stopper rigging. The stopper is then tried for tightness by means of a handful of sand thrown around the stopper head. In open hearth and arc electric practice, the ladle is carried by crane, and held under the spout of the furnace for tapping. Usually in the open hearth, and sometimes in the electric furnace, additions of deoxidizers or recarburizers are added to the ladle during the tapping. In Bessemer practice, the ladle is carried to the converter by a crane. The converter is tilted to tap into the ladle, and the necessary recarburizer additions are made during the transfer. When ladles are used in the crucible practice, they are called mixing ladles. They are supported on carriages or buggies running on rails straddling the pouring pit which contains the molds. The ladle is then run to some convenient point to which the individual crucibles are taken and teemed by hand with tongs into the ladle.

In all cases where the entire heat of steel has been tapped or transferred into the ladle, it is assumed to be at the proper temperature for pouring, or a somewhat higher temperature, uniform throughout, and covered with a slag blanket to protect the metal from oxidation and chilling by the air. If the temperature is too high, the ladle is held for a length of time calculated to cool it to the proper temperature. The metal is then poured into the molds.

After pouring the ladle is immediately dumped to clean out slag and residual metal, and cooled off, often with water. When cold the ladle is chipped free of slag and metal preparatory to repatching the lining. Sometimes when the metal is cold, a shell of steel, known as a *skull*, is left in the ladle. This must be removed, and often causes quite large repairs, because it tends to pull with it much of the refractory lining with which it is in contact. The amount of skull left in the ladle is often taken as an indication of the temperature of the metal.

When the ladle has been cleaned of slag and metal, it is patched with mortar and sometimes with brick, and a new nozzle and stopper set. It is then ready for drying for the next heat. With minor repairs after each heat, brick lined ladles run a limited number of heats per lining, after which the inner course of brick must be entirely torn out and replaced.

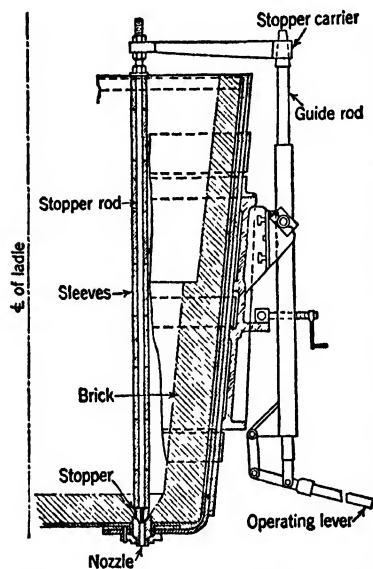


Fig. 1—Section of a Bottom Pour Ladle (Boylston).

Ingot Practice—Assuming the heat of steel in the ladle to be at the proper pouring temperature, the process of pouring into the molds to form a sound ingot may appear at first glance to be a very simple matter. On the contrary the operation involves a great many complex reactions, the control of which is extremely important since in pouring the ingot the steel maker is virtually laying the foundation for everything which comes after. To comprehend this clearly, it is necessary to look briefly into the mechanism of the freezing of steel.

Freezing of Steel—In the molten condition steel is practically a uniform liquid, every part being like every other part. The various elements in addition to iron, such as carbon, manganese, silicon, phosphorus, sulphur, chromium, nickel and vanadium, are all uniformly in solution in the iron or practically so. However, upon freezing, the steel no longer has this complete uniformity. The reason for this is that like all other metals, steel crystallizes upon freezing, and in so doing, solidifies selectively. Solidification begins with the formation of crystals rich in the element which raises the freezing point of the alloy. The liquid left between the crystals is rich in those elements which lower the melting point of the alloy. If cooling is fast, they are quickly trapped between the original crystals, which on account of their tree-like form, are called dendrites, and in this condition are not harmful, since they are well distributed and in a condition which can readily be broken up in hot working. However, if cooling is quite slow, the low melting constituents will remain liquid for a sufficient length of time to allow

them to gather into certain parts of the ingot, particularly the axis. The gathering of these low melting constituents is called segregation. The extent and location of such segregations depend upon the speed of freezing, which in turn depends upon the sectional size of the ingot, pouring temperature, rate of pouring, and the design of the mold.

Upon freezing steel contracts or shrinks, so if the mold is poured full of molten steel, it will no longer be full after the steel is solidified. It will be found that the steel has not simply settled down, leaving an air space above it, but that the location and shape of this air space or *shrinkage cavity* depends largely upon the shape and design of the mold.

Mechanism of Freezing—The first metal freezing against the mold wall shrinks slowly, and this shrinkage is immediately filled by the molten metal in contact with it. Each succeeding layer freezing parallel to the mold surface similarly shrinks and robs molten metal from the center. In a cylindrical or prismatic mold, the steel freezes progressively to the walls. The molten pool in the center gradually sinks downward as it feeds these shrinking walls. This continues as long as the chilling effect of the mold wall is felt in the molten pool. When this effect is no longer felt, the molten metal freezes slowly throughout, and shrinks downward. The net result is an ingot with sound walls, with an axial cavity, or pipe, extending a considerable distance downward. This pipe can be made to extend deeper into the ingot by designing the mold large at the bottom and small at the top (big end down), and it can be made much shallower by reversing the procedure and designing the mold big end up. Fig. 2 shows sections of big end up and big end down molds and the difference in freezing behavior.

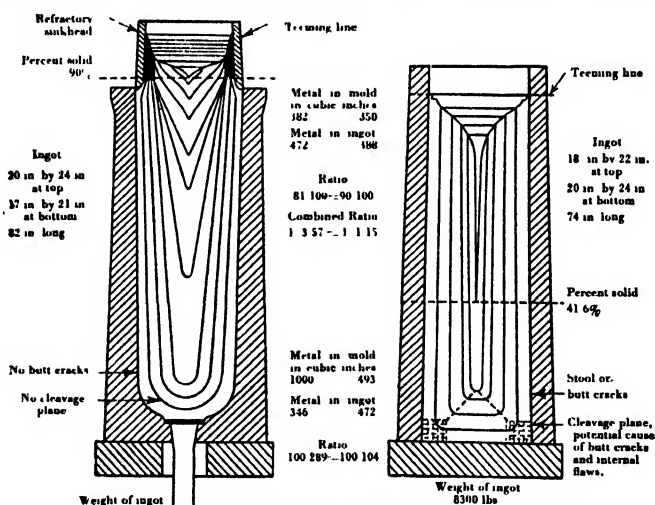


Fig. 2—Section of Big End Up and Big End Down Molds.

Another result of the shrinkage of steel during freezing is the behavior of the surface metal. The first molten metal coming in contact with the mold wall freezes instantly. As it does so, it also shrinks and the surface metal tends to pull away from the mold wall, leaving an air gap. Therefore, the shell of metal is now supporting the molten metal inside and is no longer in direct contact with the mold wall. This has two disadvantages: 1. It greatly reduces the chilling effect of the mold; and 2. it introduces the danger of the molten metal rupturing the shell, resulting in bleeding, and consequently a rough or cracked ingot. The round sectioned mold introduces the greatest hazard in this respect. The square mold is a considerable improvement over the round, and the fluted or corrugated mold is an additional improvement over the square.

Therefore, the design of the mold is a very important factor in the production of sound ingots. It should be mentioned, however, that the conditions described can be modified by adjustments in the pouring temperature and pouring rate, factors which must not be overlooked when discussing shrinkage and segregation.

Another characteristic of steel is that it liberates a certain amount of absorbed gas during freezing. The amount depends upon the method of manufacture. Killed steel liberates a comparatively small amount, but open or rimming steel evolves quite large quantities of gas. The evolution of this gas must be controlled by proper deoxidation methods and a suitable amount of chill to keep the resulting blowholes deep under the surface where they will be comparatively harmless.

Thus far the conditions considered affect the internal structure of the ingot. The surface condition is of equal importance, as this determines the amount of expensive chipping or grinding which must be done on the resulting billet to insure a finished bar or forging free from surface defects. To produce a good ingot surface requires a good mold surface, and a minimum of splashing during the pouring of the ingot. This is sometimes accomplished by pouring the ingots from the bottom by means of a gate or runner, often in groups. This practice is called bottom pouring and is used principally in the production of forging ingots. The use of mold washes also improves ingot surface.

Mold Design—Ingot molds are generally cast iron although a few steel molds have been used with indifferent success. Water cooled molds have also been used to a limited extent, although these are still in the experimental stage. The small molds ranging from 3-6 in. sq. are often of the split or two-piece type to facilitate stripping. Molds over 6 in. are usually of the solid type, although some larger split molds are used. The solid molds fall into two general classes: Big end up and big end down. Big end down molds have the advantages of lower first cost and easier stripping. Big end up molds have the advantage of higher yields and sounder steel. Molds may be of various shapes such as square, rectangular, corrugated round, 8-sides fluted, or 12-sides. Big end down molds are open at both ends and are set upon a cast iron or copper stool which forms the bottom of the mold. Big end up molds usually have a round hole in the bottom which is closed with a tapered plug, as in the Gathmann type.

Setting the Molds—The method of setting the mold preparatory to pouring varies in different plants. In most open hearth plants molds are set on buggies, three to each car, and are spotted along a pouring platform on which the ladle man stands during the pouring of a heat. In some plants the molds are set on the floor, while in others they are set in pits so that the ladle man needs no platform.

Molds are carefully cleaned, then usually coated with a mold wash, either a tar compound or whitewash, or smoked with burned rosin. In many plants a *hot top* is used on the top of the mold to eliminate pipe. This is an insulating shell made of brick or sand which keeps a reservoir of hot metal in the top of the ingot, thus the pipe cavity is progressively fed as the ingot shrinks during freezing.

In bottom pouring, the stools are especially designed with a hole in the center into which is inserted a brick cup. This cup is connected to a built up tube of brick, known as a runner, which in turn is elbowed to a vertical brick runner into which the metal is poured.

Pouring Operation—The ladle is spotted over the properly set mold, or over the runner in bottom pouring. The steel is carefully poured at the proper rate which is often determined by a watch. Sometimes instead of pouring direct into the mold, the steel is poured into a pouring box which has one or more nozzles in the bottom. This pouring box is used for the purpose of reducing pressure and thus eliminating splashing during the pouring of the ingot.

Where hot tops are used, it is often the practice immediately after the ingot has been poured to cover the top with some insulating material to assist in keeping the top metal molten. When the ingots are entirely frozen, or *set*, they are removed from the mold, or *stripped*. In the case of car type molds special stripping cranes are in use, adapted either to big end up or big end down practice. With the ordinary pit practice, stripping is done by hand with the assistance of the crane.

The cooling of the ingot after stripping, particularly in the higher alloy steels, is of considerable importance and must be done carefully to prevent cracks. Usually when the ingots are not taken hot direct to a soaking pit, they are buried in ashes or other insulating material to insure slow cooling.

The Manufacture of Hot and Cold Rolled Strip and Sheets*

Composition Suitable for the Various Grades—Low carbon steels are generally considered those with a carbon content less than 0.20%. Often those unfamiliar with the sheet and tin plate industry are inclined to regard variations in composition within the low carbon range as relatively unimportant, and of only minor influence on the physical characteristics of the steel. In fact, it might be pertinent to state that the whole field of low carbon steel, particularly as it relates to the manufacture of sheets and tin plate, has been accorded much less attention on the part of educational and research institutions than its economic importance deserves.

Actually, what might be considered small differences in carbon, manganese, phosphorus, and sulphur may spell success or failure in the ultimate use for which the product is intended. The succeeding paragraphs will attempt to explain, in a general way, the influence of the common elements in steel, and what considerations must be taken into account when producing sheets for specific requirements, for, as in so many other branches of the steel industry, it is impossible in most instances to ship stock sheets; the peculiarities of each requirement must be analyzed, and a special product manufactured to meet it.

Hot Rolled Sheets—For convenience, the product of the old style hand sheet mills will be called "hot rolled sheets" to differentiate them from hot rolled strip sheets as produced on a continuous hot strip mill, and cold reduced sheets as produced on the continuous cold mills.

Formerly, the hot sheet mills rolled all of their product from sheet bar. With the advent of the continuous hot strip mills, many producers with both types of equipment commenced to substitute strip packs for the intermediate breakdowns rolled from bar. This resulted in improved surface, more uniform gage, increased production, and, to some extent, relieved certain limitations as to chemistry. However, the same general principles still apply.

In the pack rolling of sheets in the lighter gages (20 gage and lighter), the pressure of the rolls tends to weld the sheets together. This effect can be counteracted by adding phosphorus to the steel, which is sometimes done, particularly for 26 gage and lighter. However, phosphorus is a hardening element, and, in work where ease of forming or deep drawing are a requisite, it is often a hindrance.

Manganese is important in improving surface toughness in drawing, but it apparently can contribute to blisters in pickling and galvanizing when its presence exceeds certain limits. In rimmed steel, from which the major tonnage of sheets is now rolled, the surface tends to be open or porous in pack rolling. If the manganese falls much below 0.20%, this characteristic is accentuated, and, where surface is of prime importance, it is objectionable.

Carbon acts as a deterrent to grain growth in box annealing, and, except for vitreous enameling sheets, it is desirable to keep the carbon content over 0.03% by check analysis.

Automobile sheets produced on the hand mills are rolled from rimmed steel with a ladle analysis approximating 0.05-0.08% carbon, 0.25-0.50% manganese, phosphorus under 0.030%, and sulphur under 0.050%. Here, the manganese will assist in producing a tight surface; the carbon and manganese together will result in a fairly small grain size with the desired toughness and ductility, and, after drawing, the stamping will have a smooth finish.

Typical analyses for various products are as follows:

	Carbon, %	Manganese, %	Phosphorus, %	Sulphur, %	Copper, %
Ordinary requirements, stock, mild forming.....	0.05-0.08	0.20-0.35	Depending on gage	Low as Possible	As Specified
Deep drawing and automobile sheets	0.05-0.08	0.25-0.50	0.030 Max.	"	
Surface important, painting, lithographing	0.05-0.08	0.25-0.50	Depending on gage	"	As Specified
Galvanizing	0.04-0.07	0.15-0.30	"	"	"
Vitreous enameling.....	0.03 Max.	0.10 Max.	Low as poss.	"	

Higher carbon steels are used for frames and other structural parts, but as the carbon is increased the workability decreases, and 0.35% carbon appears to be the

*Prepared by the Subcommittee on Sheet and Strip. The membership was as follows: J. H. Nead, Chairman; E. L. Kerschbaum, J. E. Angle, T. F. Oil, R. W. E. Leiter.

upper limit of a steel which may be bent cold to a right angle around a radius equal to the thickness of the sheet. This limit can be raised by suitable annealing practice.

In the discussion of types of steel for various products, certain modifications of the above will be cited, since killed steels, in particular instances, give much better results than rimmed.

Hot Rolled Strip Sheets—Hot rolled strip in sheet widths (24 in. and wider) is commonly rolled as light as 18 gage. With proper slab conditioning, and good mill practice, a smooth tight surface can be obtained regardless of the analysis of the steel. Therefore, certain chemical limitations are removed.

Rimmed steel is generally used for hot rolled strip. Typical analyses will approximate 0.05-0.08 carbon, 0.25-0.50 manganese, 0.03 phosphorus, max., by ladle analysis. Where only mild forming is involved, a certain latitude is permissible, particularly in respect to phosphorus and sulphur. In sheets for deep drawing, the phosphorus, in particular, and the sulphur are held as low as possible. Further variations in physical properties necessary to fit the requirement are usually secured by subsequent treatments such as normalizing, open annealing, box annealing, cold rolling, or pickling.

Cold Reduced Sheets—Steel quality and chemical analysis are probably of more importance in producing a successful deep drawing sheet by the cold reduction process than by hot rolling. This may be due partly to the fact that cold reduced sheets, after final temper rolling, are in a state of unstable equilibrium which increases the sensitivity of the steel to certain variables. Also of importance, no doubt, is the fact that the difference between success and failure may be the loss of one stamping, more or less, out of a hundred. There is no question that the most careful control from blast furnace to final processing is necessary for the manufacture of a consistently satisfactory deep drawing sheet.

Factors to be considered in selecting the analysis to be used for cold reduced deep drawing sheets are:

(a) *Size and Shape of the Drawn Part*—Large deep stampings such as automobile quarter panels require a relatively soft, and, at the same time, ductile sheet. Owing to the size and awkward shape of the part, a stiff or hard steel will wrinkle in the die, and, if increased hold down pressure is applied, breakage will usually result. For such work, the carbon and manganese may be held to the low side of a 0.05-0.08 carbon, 0.25-0.40 manganese specification. In this particular respect, cold rolled sheets produced on the hand mills, with a normalize and box anneal treatment, have an advantage over the cold reduced box anneal sheet, since, for the same analysis, they sometimes tend to be softer; but other considerations, such as perfection of surface, and especially uniformity of thickness, tend to offset any possible advantage of greater softness.

Small deep stampings, in which wrinkling is not a hazard, permit of slightly higher manganese content with a resultant finer grain size and improved ductility.

(b) *Surface After Drawing*—In deep drawn parts, where surface is of importance, it is often necessary to exercise as much control as possible over the grain size of the finished product, since a relatively large grain will result in a type of "orange peel." Automobile fenders are a good example of a part where the surface after drawing demands a small grain. Expressed in terms of the A.S.T.M. grain size chart, a No. 7 or 8 grain is usually preferable. Although treatment is important in the control of grain size, manganese content is also important.

Phosphorus is especially harmful in deep drawing work, and is held as low as possible. Sulphur is generally believed to be detrimental in deep drawing sheets, but its effect is not so clearly known as is the case with phosphorus.

There appears to be an increasing demand for steels of the low alloy high strength type,¹ especially in the field of transportation.

These steels have a 50,000-60,000 psi. minimum yield strength, and 65,000-70,000 psi. minimum tensile strength; the maximum tensile strength will seldom exceed 85,000 psi. The minimum elongation is usually around 20%. These steels are more often found in the heavier gages, but recently sheets as light as 24 gage have been rolled.

Various elements and combinations of elements are used as strengtheners in this type of steel to obtain a proper balance. The ranges are as follows:

C	Mn	P	S	Si	Cr	Cu	Ni	Mo
0.12 Max.	0.20-1.00	Residual to 0.200	0.045 Max.	Residual to 1.00	None to 1.5	0.30-1.75	None to 2.25	None to 0.12

Types of Steel—The terms, "rimmed" or "killed," apply to the action, or lack of action, of the steel in the molds during solidification of the ingots. Steels containing up to 0.30% carbon can be either rimmed or killed, as desired; but above 0.30% carbon the steels are killed. Alloy steels, with the exception of copper-bearing steels, are usually "killed" or deoxidized in the furnace, ladle or molds.

Except for special analyses, rimming steel is used for the majority of sheet and strip applications. In certain work, such as deep drawing and forming, its softness and ductility are particularly well suited. There are other applications where the type of steel would make no particular difference; but, as might be expected, there are certain specifications where killed steel is to be preferred.

A rimmed steel is a natural steel in that the dissolved gases are allowed to separate as the liquid metal freezes, and rise to the surface in an effervescent action which is controlled by the addition of aluminum or other deoxidizers to the ladle or ingot. The rimming action progresses until the ingot is capped or freezes over the top. Its effect, when properly carried out, is to produce a thick skinned ingot with a heavy "rim" which may be hot rolled with a minimum of surface defects. The rimming action also reduces the carbon, and to a lesser extent the manganese, in the outer or rim portion of the ingot.

The factors controlling the rimming action are composition or analysis of the steel, furnace practice, and deoxidation practice in the ladle and the molds. A deep etched cross section of a piece of rimmed steel shows a characteristic rim and core (or segregate), except at the extreme lower part of the ingot. This segregation of metalloids accounts for variations in analysis found in different parts of a sheet or order.^{2, 3}

"Killed" steels are made by adding a sufficient quantity of the various deoxidizers to the furnace, ladle, or molds. The deoxidizing materials have a greater affinity for oxygen than iron or manganese, thus forming more stable compounds, and these may be partially eliminated during subsequent processing and cropping. As little gas is formed, either due to reactions or to gases coming out of solution: the ingot top freezes rapidly and the ingot solidifies as a comparatively homogeneous mass. Little segregation takes place; and analyses of the various parts of the ingot are more uniform than in a rimmed steel.

These characteristic differences in the two types of steels have certain effects on the sheet and strip produced from them. The rimmed steel has a thicker skin, which results in a sheet comparatively free from surface defects. A killed steel generally has a more sensitive skin which may or may not be ruptured during hot reduction in the mills from the ingot to the bar or slab, and this may result in either surface laminations or seams. For this reason, when surface is important, rimmed steels are almost universally used.

There are certain advantages in favor of the killed steels, such as uniformity of analysis; and a properly killed and processed steel is comparatively free from aging. However, for the same carbon and manganese content, the killed steel is harder than the rimmed steel.

In sheets hot rolled on the hand mills, killed steel is decidedly superior to rimmed in producing a smooth tight surface free from orange peel. Its use is, therefore, to be preferred for hot rolled annealed furniture stock, lithographing and japanning stock, and blued stove pipe sheets. The uniformity of its properties from edge to center also makes it desirable for stretcher leveling.

Its disadvantages lie in its somewhat higher hardness for the same analysis, and its susceptibility to seams and skin laminations.

In the heavier gages, such as are rolled on the hot strip mill, many specifications require check analyses. Here, killed steels are often used because the sheet analysis can usually be depended upon to correspond closely to the ladle analysis.

Killed steels are not widely used at present in cold reduced sheets except, perhaps, for stretcher leveling. Even here, equally good results can be secured with rimmed steel by heavy top cropping, or diverting the top portion of the ingot to other work.

The characteristics of rimmed steel leave much to be desired, especially in deep drawing cold reduced sheets. Although with present methods of control greater uniformity from heat to heat is now possible, there still remains the variation in the ingot (top to bottom as well as rim to core), and the variation from ingot to ingot within a heat. Differences between top and bottom may be somewhat lessened if desired by diverting the top portion of the ingot to other work. However, such diversion is not always economical and, at best, is not desirable. In straightaway rolling,

the rimmed area is usually in the hold down of the die where it is not detrimental.

Perhaps the most objectionable characteristic of rimmed steel in cold reduced sheets is the aging which occurs after the final temper rolling. This exhibits itself in the return of the tendency to stretcher strain, in an appreciable increase in hardness and yield strength, and in a decided decrease in ductility, as measured by cup tests, and elongation in tensile testing. Aging begins immediately after the final cold working, but it is usually not serious until after 3 or 4 weeks. The extent to which it affects performance depends to a considerable extent on the properties of the steel at the time of temper rolling. For example, a 20 gage sheet with 45 Rockwell B hardness and .42 Olsen cup may age harden to 50 Rockwell and .400 Olsen, and still draw satisfactorily. However, if the initial Rockwell had been 50 and the Olsen .400, and the same amount of aging had occurred, it is possible that breakage would result on certain difficult jobs.

The theory of age hardening has been fairly well established, and nonaging steels have been manufactured. It is difficult, however, to produce a soft nonaging steel suitable for sheets without excessive losses due to surface defects, and which responds satisfactorily to annealing.

In hot dip galvanizing, tinning, or terne coating, the temperature of the metal is high enough to effect complete aging in many cases. This may or may not be detrimental, depending on the use. It can be overcome by special treatments which eliminate the final temper rolling, or there are requirements which can best be met by using a low metalloid steel. In certain tin plate applications, where stiffness and rigidity are necessary, rimmed or killed Bessemer steel is often used.

Classification of Sheet and Strip—The following table gives the size range of sheet and strip. Due to increased accuracy of the strip mill, permitting wider sheets, the difference between sheet and strip based on widths has become an arbitrary figure.

Standard Classification of Flat Rolled Carbon Steel

Width, Inch	Thickness, inch						
	.2500 or Thicker	2499 to 1875	1874 to 0568	0567 to 0344	.0343 to 0255	0254 to .0142	.0141 or Thinner
<i>Hot Rolled</i>							
Up to 3½ inclusive	Bar	Strip	Strip	Strip	Strip	Sheet	Sheet
Over 3½-6 inclusive	Bar	Strip	Strip	Strip	Sheet	Sheet	Sheet
Over 6-12 inclusive	Plate	Strip	Strip	Sheet	Sheet	Sheet	Sheet
Over 12-32 inclusive	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	T.M. Black
Over 32-48 inclusive	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	Sheet
Over 48.....	Plate	Plate	Sheet	Sheet	Sheet	Sheet	.....
<i>Cold Rolled</i>							
Up to 12 inclusive	Strip	Strip					
Over 12-24 inclusive	Strip ¹	Strip ¹					
Over 24-32 inclusive	Sheet ²	T.M. Black ²					
Over 32.....	Sheet	T.M. Black					
		Sheet					

¹ If special edge or finish, or temper as in A.S.T.M. Spec. A-109.

² If no special edge, finish, or temper.

Hot Rolling—Sheets and strip can either be hot rolled directly to the desired thickness or hot rolled to an intermediate thickness and then cold rolled to the desired thickness. The latter process is used if improved surface finish or special temper and properties are desired. Hot rolling is here classified as including rolling operations in which the material is heated before passing between the rolls. Sheets are hot rolled by a number of methods: 1. On broad hot strip mills from slabs; 2. On hand mills from sheet bar; and 3. On hand mills from broad strip sheared breakdowns.

1. Broad Hot Strip Practice—The rolling of broad hot strip or "sheets in coils" has been a continuous development since 1927, when the first mill was built capable of rolling a strip over 24 in. wide. The strip process differs from the sheet process in that in the former the reduction is performed in long lengths, which are subsequently cut up or coiled, while in the latter the reductions are performed in unit lengths or a small multiple. In strip rolling a slab ingot is cast and rolled to a slab of 3-6 in. in thickness and of a width and length suitable for charging into the slab

reheating furnace, where it is brought up to a temperature of 2200-2300°F. for rolling.

The broad strip mills consist of a roughing train and finishing train set in tandem, the finishing train being set on close centers so that the strip is in all of the finishing stands at the same time. The number of roll stands can be varied to suit the variety of products produced in any given mill, but usually vary from 4-7 roughing stands and 4-6 finishing stands. The roughing train usually consists of a two high scale breaker to break up the scale on the surface of the slab, a spreading mill to spread the slab to the desired width of strip, after which it is turned 90° and squeezed to straighten the edges. The slab is then rolled to the desired rough bar thickness in the balance of the roughing mills which are usually of the four high type and equipped with vertical edging rolls to hold an accurate width in the bar. In the roughing reductions, the slabs are usually sprayed with high pressure water to descale the surface of the slab as it progresses through the mills. As a modification in practice, the slab can be rolled to a rough down bar on a reversing universal mill. After roughing, the bar goes through another scale breaker and high pressure spray and into the four high hot strip stands where it is reduced to the desired thickness. These mills are so synchronized as to speed that each successive mill takes the strip at exactly the same speed that the preceding mill is delivering. The delivery speed varies from 1000-2100 f.p.m. The finishing temperature can be varied over a considerable range by varying the slab heating temperature and holding time ahead of the strip mill. In general, the finishing temperature varies from 1300-1600°F. and must be closely controlled wherever it is desired in order to keep uniform thickness throughout the length.

After the strip is delivered from the last stand, it can be either coiled or cut to length, flattened by leveling, and piled. It must be coiled or piled at a temperature sufficiently low so that appreciable grain growth^a does not take place.

The product of the hot strip mill has a wide variety of uses. It may be cut as breakdowns for a hot sheet mill if a thinner gage is desired than can be produced on the hot strip mill. It may be shipped directly after cutting and leveling, or after normalizing and pickling if better properties are necessary for the particular requirements under consideration. After pickling in coils, it may be used for the production of thinner gages than can be rolled directly on the hot strip mill by continuous cold reduction processes and also for applications where a better and smoother surface than can be obtained on a hot strip mill is required.

The process for narrow strip is similar to broad strip, except that lighter equipment can be used and less power is needed. The wider the strip desired, the more massive the equipment must be and the greater the power requirements, which are approximately 400-500 connected hp. per in. of width capacity.

2. Sheet Bar Practice—The sheet bar practice for the production of hot rolled sheets involves the rolling of an ingot to a rectangular sheet bar which is usually 8 or 12 in. in width and of a thickness that will allow cross rolling on a hot mill to the desired thickness and length. The sheet bar is cut so that its length is slightly greater than the width of the desired sheet. The hot mill consists of two stands of rolls, known as the roughing and the finishing stands, and two furnaces known as the "pair" furnace (so named because the bars are withdrawn and roughed out in pairs) and the reheating furnace where, after matching the rough outs are reheated for finishing. The rolls are of chilled iron and are driven by constant speed motors, or in some extremely old installations, by a steam engine. The sheet bars are heated in the pair furnace to a temperature of 1300-1600°F., depending on the grade of steel and surface finish required, and rolled in pairs to a breakdown gage using single passes and then matching the bars and rolling in pairs until the breakdown gage is reached. At this point the breakdowns are matched, reheated, and finished to the desired sheet thickness. This general method can be modified by pickling the bars and breakdowns to produce a smoother and more uniform surface finish. Also, sheets 0.025 in. and thinner are usually made "double," that is, the matched breakdowns are folded over on themselves before reheating.

After hot rolling to the desired thickness, the sheets in packs are trimmed to the desired dimensions and separated and are ready for further processing operations.

3. Sheared Breakdown Practice—This process is somewhat like the sheet bar practice except that the breakdowns are sheared from broad hot rolled strip of a width slightly greater than that of the desired sheet and of a length sufficient to make a sheet of the desired gage and length. The breakdown operation is eliminated and consequently only one stand of finishing rolls is necessary. This practice lends itself readily to the utilization of continuous pack heating furnaces and mechanized

feeding and catching tables. It also lends itself to the use of single three high mills which roll both under and over the middle roll (from both sides of the mill) with greater reductions and increased speed and also the same type three high mills set up in a tandem train. Pickling the sheared breakdowns before hot rolling improves the smoothness and uniformity of the surface finish. As in the sheet bar practice, after hot rolling the sheets are trimmed on all sides and separated and are ready for further processing.

Cold Rolling—Sheets and strip are cold reduced to the desired thickness for several reasons: 1. To obtain the desired surface finish; 2. To impart desired physical properties; and 3. To make gages thinner than the hot strip mill can produce economically.

The cold reduction can be accomplished either in unit lengths or in coils, but it is more economical from a yield standpoint to perform the reduction in coils.

There are numerous types of equipment for performing the cold reduction, but as in the case of hot strip mills, the wider the material to be cold reduced and the thinner the desired gage, the more rigid the mill, and the more power required. In narrow widths (under 20 in.) the reductions can be performed conveniently on two-high mills, but in the wider widths the four-high mill is used almost entirely. As the width is increased or the thickness decreased, the diameter of the backing up rolls is increased. The working roll diameter is kept as large as is compatible with the maximum screw pressure allowable.

The amount of cold reduction performed is governed largely by the application under consideration. For example, sheets and strips for drawing applications are cold reduced from 30-70% in thickness. Tin plate may be reduced as much as 90% in thickness. Increasing amounts of cold reduction will tend to make the resulting sheet and strip finer grained and harder after annealing.

Equipment for cold reducing steel sheets and strips is available which makes use of the following applications of power to effect the desired reduction: (1) All power applied to the working rolls; (2) all power applied as forward and back tension; (3) power applied partly to the working rolls and partly as forward tension; and (4) power applied to the working rolls, also as forward and back tension.

1. *All Power on Working Rolls*—The cold tandem sheet mill or single stand mill for the reduction of strip breakdowns in units is an example of this method of application of power. This method involves the production of more scrap due to the multiplicity of ends sheared from the sheets when heavy reductions are performed. This method is also used to a great extent in skin rolling sheets after annealing to remove the tendency to form stretcher strains when drawn. Skin rolling involves little reduction in thickness of the section.

2. *All Power Applied as Forward and Back Tension*—This method of application of power is employed in the "Steckel mill" which is a four high mill with small working rolls for rolling coiled material. This type of mill is limited in the amount of cold reduction that can be taken in a given pass, but is built to reverse and can reduce any number of passes and to any practical thickness desired. The small diameter working rolls present a small surface area and hence wear rapidly and must be replaced frequently or whenever the surface of the strip being rolled is unsatisfactory. This mill is rather popular for extremely hard or thin materials and high priced specialties with extremely close tolerances in thickness variation.

3. *Power Applied Partly to the Working Rolls and Partly as Forward Tension*—This method of reduction is typical of by far the greater number of tandem cold reduction mills utilizing coil stock. In general, the reduction mill is made up from 3-5 tandem stands of four high mills with a powerful reel producing forward tension. The capacity of this type mill is governed largely by the thickness and width being rolled, and the delivery speed of the mill. Cold mills delivering tin plate gages deliver up to 1500 f.p.m., whereas the heavier sheet gages are usually delivered up to 700 f.p.m. This type mill has the advantage of high capacity and low labor and roll cost, although the investment is high. Disadvantages are lack of flexibility for rapid section changes and the fact that material being rolled receives a fixed and limited number of passes.

4. *Power Applied to Working Rolls, also as Forward and Back Tension*—This application of power is exemplified by the single stand reversing mill. This type mill differs radically from the Steckel mill in that it is not limited in the amount of reduction per pass as is the Steckel type. This mill is advantageous from the standpoint of flexibility of number of passes and requires less investment cost and floor space than a tandem mill. The energy expended in back tension is regenerated by

driving the back reel as a generator against the line load, the back tension also serving to reduce the screw pressure and the net energy required for the deformation. On the other hand, the investment per ton capacity, labor cost, and roll cost is higher than for a tandem mill.

Annealing of Sheets and Strips—It is necessary to perform some manner of annealing operation on hot reduced and cold reduced sheet and strip, unless a hard temper is desired. This may not be necessary on some hot rolled strip finished at 1500-1600°F. or over and coiled hot so that an annealing is accomplished in the coil. If the sheets are reduced to gage below the recrystallization temperature as they are on the sheet bar finishing mill or cold reduction practice, the grain structure is fragmented and plastically deformed by slip resulting in preferred orientation.

There are a number of softening operations used in sheet and strip production, the most important of which are: (1) The cold strain, low temperature recrystallization anneal; (2) the normalizing operation; and (3) the stress relieving anneal.

1. The Cold Strain, Low Temperature Recrystallization Anneal—This process may be used on material cold reduced in excess of 30% (includes hot rolled material finished at a low enough temperature to give the equivalent strain of material rolled cold). This type of annealing (also known as "processing annealing") is carried out by placing stacks of sheets or coils on a bottom or plate and then covering the pile. The charge is then heated to the desired temperature, which may vary from 1200-1400°F., and allowed to soak until the temperature is uniform throughout the charge, after which it is allowed to cool to the desired temperature before uncovering.

This annealing may be carried out in stationary furnaces in which the charge, including plate and cover, is inserted in the furnace for the necessary heating and soaking and then removed for cooling, or in the radiant tube type furnace in which the plate is stationary and the furnace is lifted from charge to charge for the necessary heating and soaking. The charge may vary from 5-100 tons, depending on the size sheet or strip and height of stack. The source of heat may be gas, coal, oil, or electricity.

Material that has been cold reduced or descaled before annealing is usually annealed in a protective atmosphere or "bright annealed" in order to prevent the formation of oxide on the sheet during the heating, soaking, and cooling cycle. This protective atmosphere is ordinarily produced by partially burning natural gas or butane to a gas composition that is slightly reducing to iron but will not break down further and deposit carbon at the annealing temperature. Most of the water vapor produced from the partial burning is removed from the protective gas by refrigeration. Material that is desired with an oxide finish is either annealed without the protective atmosphere or "steam blued" by adding steam under the cover after removal of the charge from the furnace when the temperature has dropped to 1000-1100°F.

2. Normalizing—The normalizing operation consists of heating the sheet or strip to a temperature above the upper critical or A_3 point (approximately 1650°F.) and cooling to room temperature. This recrystallizes and refines the grain structure through the medium of a phase transformation. The normalizing operation is utilized to the greatest extent on hot reduced material to produce improved drawing properties, as in many cases a low temperature box anneal would result in critical grain growth due to a low residual strain in the hot reduced product.

Normalizing furnaces for sheets are usually of the chain type, roller type, or walking beam type. Fuels may be gas, oil, or electricity. With electric furnaces or muffle types, it is possible to "bright normalize" by using an inert or a reducing atmosphere to protect the surface of the strip from oxidation.

The grain size and hardness of normalized material can be controlled within limits by varying the soaking time above the A_3 point and also the cooling rate from the A_3 to the A_1 point.¹⁰

3. Stress-Relieving Anneal—This annealing operation is a low temperature pack or box anneal utilized to remove the internal stresses, produced by the rapid cooling in the normalizing operation and in leveling or light rolling operations after normalizing, in order to improve the drawing properties. This operation is commonly known as a "second or white anneal" and is carried out in the same manner and with the same equipment as the cold strain box anneal except that the temperature of annealing is in the range of 950-1200°F. A protective atmosphere can be used under the cover to prevent oxidation or the charge may be steam blued as desired.

Typical values of physical properties of mild steel sheets and strips after the annealing operations referred to are given in the following tabulation:

	Yield Points, psi.	Tensile Strength, psi.	% Elong. in 2 in.	Rockwell	Olsen Cup (.040 thick)
Hot rolled (sheets)	50,000	68,000	10	B-70	.200
Hot rolled (cold strip)	45,000	55,000	30	B-60	.350
Hot rolled + normalize	38,000	52,000	32	B-55	.365
Hot rolled + 2nd anneal	30,000	48,000	38	B-50	.390
Hot rolled + cold reduced	85,000	85,000	4	B-90	.120
Hot rolled + bright anneal	28,000	45,000	42	B-45	.410
Hot rolled + normalized	40,000	54,000	30	B-60	.360
Hot rolled + normalized + 2nd anneal	32,000	50,000	38	B-52	.390

Surface Characteristics—The surface texture of sheets and strip can be varied between rather wide limits. For chromium plating and similar uses, a smooth bright surface is necessary, but for vitreous enameling and many drawing operations, a certain dullness or roughness of surface is more suitable. In the case of vitreous enameling, the roughness improves adherence; and in certain drawing operations where heavy pressures are developed, the duller type of surface draws better. It also appears to aid in the distribution of the draw. Minor surface imperfections and slight strains are not so noticeable on a dull surface as on a bright one. However, the surface should not be so dull that subsequent finishes will not cover.

The smooth finish can be obtained by grinding and polishing the rolls. The dull surface can be obtained in several ways. A chill cast or alloy cast iron roll can be dulled by acid etching the ground surface. This develops the dendritic structure by removing segregated areas, and leaves a pattern which can be imprinted on the surface of sheet or strip, resulting in a light dullness. This pattern will vary from roll to roll because of differences in the size of the dendrites.

Since a hardened steel roll does not have a massive structure which can be developed by etching, it is necessary to dull the roll by mechanical means. This is done with either sand or shot blasting equipment which can be controlled to give a uniform dullness of any desired degree by varying pressure and shot size. Because of the control over dullness by this process, it is also used to a large extent on chill cast rolls.

The surface can be dulled in the last stand of a tandem cold strip mill before annealing, and the sheet can be either skin rolled dull or bright after annealing; or the dullness can be applied to the bright sheet after annealing.

Metallic Coatings—Three types of metallic coatings are commercially applied to sheets or strip by steel manufacturers. These are zinc (galvanized sheets), tin, and terne, an alloy containing approximately 80% lead and 20% tin. In all three coatings, the hot dip method is commonly used, although sufficient work has been accomplished with the electrolytic coating of zinc and tin to indicate that it is commercially possible. For information about these methods, see the articles in this Handbook on Zinc Coatings and Tinning of Steel.

Testing and Inspection—*Drawing Factors and Hazards*—Appearances of a number of strips or sheets from different sources may be quite similar; but actually there are many ways of obtaining substantially the same appearance with major or minor variations in properties. Each mill is limited to a certain extent by its equipment; as the processing is modified, the properties of the product vary, and yet the material may make the part satisfactorily.

At present there are many variables in testing practice and it would be almost impossible to prepare "standards" in all tests which would meet all contingencies to the satisfaction of both producer and consumer. There are many cases of breakage in drawing operations where the material is not at fault. The die practice may be bad, due to poor design, improper clearance, too much deformation between anneals, improper hold down or drawing adjustments, or poor lubrication. In some cases, the sheet is of too light gage for the amount of deformation it is expected to stand.

Winlock and Kelley⁴ state that: "The manner in which the draw is accomplished is, within limits, of equal, if not greater importance to the success of the operation than the physical properties of the steel itself." Montgomery⁷ points out that next to die design, lubrication is the greatest factor in producing good stampings. "Efficient lubrication of production operations will effect a greater net saving to the average stamping plant than any other single factor except die design and construction."

The actual strength of the sheet or strip for most forming and drawing jobs is comparatively low. Except in the harder tempers, where the carbon may be as high as 0.25%, the steel used for drawing jobs is S.A.E. 1010 analysis. Winlock and Kelley⁸ in regard to the strength of the material state: "Strength and rigidity are usually imparted to a stamping by designing it so that it will most effectively resist the forces imposed upon it in use by virtue of a high section modulus."

Aging is another factor influencing the drawing quality of sheets and strip. A material at the time of shipment may be perfectly suited for the job, but if it is not used within a reasonable time, and aging takes place, it is probable that increased breakage will result and surface disturbances will be present in the finished part.

The amount of aging depends on the analysis, method of manufacture of the steel, amount of skin rolling, time, temperature, and the original hardness range of the material. Whittemore⁹ using random samples over a long period of time, determined the average amount of aging in different hardness groups for different periods of time. The increase in Rockwell hardness was used as the measure of aging. On that basis he recommended that specifications make an allowance for aging.

After a material has aged to a certain extent it loses its ductility and if then worked or formed stretcher strains occur. Winlock and Laverne¹⁰ along with many others have studied "stretcher strains," "worms," or "lines of Luder." They found that this disturbance tends to occur in those parts subject to a deformation of 1.5-10% during forming. In tension the lines are low spots, in compression they are elevations. They attribute the stretcher strains to fluctuations at the yield point. Cold working by roller levelling or skin rolling generally eliminates the sharp yield point and the tendency to stretcher strain.

For a true picture of the conditions within a given sheet or strip, it is necessary to select samples with regard to the method of manufacture. In checking the analysis of strip or sheet which was "straight rolled" it is necessary to take millings from the entire cross section. If the amount of segregation is to be checked, samples should be taken from edge and center. If the sheet has been "cross rolled" from sheet bar the composite sample from end and center of the sheet will give an average analysis, and tests on the end and center of the sheet will give a check on the amount of segregation present. The same remarks are true for any test applied to sheet and strip; the samples should be taken so that the tests give a true picture of the whole strip or sheet. A certain amount of nonuniformity is to be expected. It is impossible to have identical properties in all parts of the sheet or strip especially when it is manufactured from rimming steel.

Inspection—There are certain defects which are more likely to occur on strip and sheets made by the continuous process, but there are certain defects found in sheet mill sheets that are absent on the strip product. The following is a partial list of the defects which may be found during inspection; some cause immediate rejection, others cause the material to be degraded into a lower class, or cause rejections, depending on the severity of the defect.

Annealing sticker	Grease pits	Pinchers
Bad steel	Guide scratch	Pipe
Black scratch	Handling scratch	Reel kink
Blisters	Heavy annealing border	Roll mark
Camber	Heavy to gage	Roll stop (for mill adjustment)
Chatter	Hickey	Rolled edge (guides too close)
Coil break	Hot mill scale	Scale pattern
Copper stain (pickling)	Laminations	Short
Corrugations	Light to gage	Side strains
Cutting machine scratch	Loose oxide	Slivers
Dimple (from annealing sticker)	Narrow	Strains
Dirt pits	Normalizer break	Stringer
Enter and end marks	Normalizer scale	Tandem mill scratch
Fluting	Not flat	Wavy
	Pickle house scratch	

Temper—The processing of cold rolled sheet and strip is varied to control the physical properties within the ranges found most suitable. This is done by controlling the amount of reduction, the annealing and the final amount of cold rolling after the anneal. These influencing factors are worked out in each plant according to their equipment and conditions so that the finished material will have the desired characteristics. The amount of cold work can vary from a pass through the roller leveler, which does not affect the thickness to any appreciable extent, or a pass on the skin mill with reductions up to a maximum of several per cent, to heavy cold

rolling which reduces the thickness as much as 50% or more. The increase in hardness over the annealed condition depends on the amount of cold work done after annealing, and the ductility falls off rapidly as the amount of cold work increases.

Table I gives the approximate physical properties of different tempers. The values also apply to sheets made by the cold strip process.

Table I

Approximate Physical Properties for Various Tempers of Cold Rolled Strip Steel*

(These values are given as information only and are not intended as criteria for acceptance or rejection.)

Grade or Temper	Rockwell Hardness B Scale, $\frac{1}{16}$ in. Ball	Depth of Cup for 0.050 in. Thickness of Strip, mm. ^a	Tensile Strength, ^b psi.	% Elong. in 2 in. for .050 in. Thickness of Strip ^c	Remarks
No. 1 Hard	90 \pm 6 ^d	6-7	80,000 \pm 12,000	3 \pm 2	Intended for flat blanking only
No. 2 Half Hard	80 \pm 5	7-8	64,000 \pm 8,000	9 \pm 5	Intended for easy bending up to 90° across the grain.* (No bending along the grain).
No. 3 Quarter Hard	69 \pm 5	8-9	54,000 \pm 6,000	20 \pm 7	For shallow drawing and stamping, where a very smooth surface is required. Bends 180° across the grain. Bends up to 90° along the grain.*
No. 4 Soft or Plushid	58 \pm 6	9-10½	48,000 \pm 5,000	30 \pm 6	For fairly deep drawing where no sign of surface strain is permissible. Bends 180° both ways of the grain.
No. 5 Dead Soft	45 \pm 7	10-10½ 10-11½	44,000 \pm 4,000	39 \pm 6	For deep drawing where slight stretcher strains are permissible. Also for drifting. (Erroneously called "extrusion.") Bends 180° both ways of the grain.

^aCup depth varies with thickness of strip. For grade No. 5, dead soft temper, the depth is given approximately by the formula $D = 10.5 \text{ mm.} + 6.4 \log "t"$ (t = thickness in mm.). Other tempers vary in a similar way.

^bTensile Properties are based on the standard tension test specimen for sheet metals, Fig. 7, A.S.T.M. Designation E 8, 1936 Book of A.S.T.M. Standards, Part I, p. 833.

^cElongation in 2 in. varies with the thickness of strip. For grade No. 5, dead soft temper, the percentage elongation = $41 + 10 \log "t"$ (t = thickness in mm.). Other tempers vary in a similar way.

^dFor cold strip .069 in. and thinner in thickness the Rockwell B hardness range is 96 \pm 6, with corresponding increase in tensile strength and drop in depth of cup test.

*To bend across the grain means that the crease formed by the bend shall be at right angles to the length of the cold rolling strip. To bend along the grain means that the crease formed by the bend shall be parallel with the length of the cold rolled strip.

*Tentative Specifications for Cold Rolled Strip A.S.T.M. Designation A 109-35 T.

The Tensile Test—Kenyon¹¹ points out that the "rate of strain" is the proper method of measuring the speed of testing, rather than the speed of the cross head of the testing machine. This permits a better correlation of the test data when comparing the results on samples of different gage lengths. Kenyon found that variation in the rate of strain from 0.08-0.38 in. per min. raises the yield point about 2500 psi., and lowers the per cent total elongation, both in 2 and 4 in., about 3%. Increased rate of strain also lowers the per cent "uniform" elongation. Although total elongation is the usual value recorded, the "uniform" elongation is truly characteristic of the material while the total elongation is not, due to the disturbing effect of the shape of the specimen. Kenyon suggests measuring this value on the "stress strain" curve as drawn with a 10 X extensometer. This measurement is made horizontally from the start of the curve, to where the load ceases to increase. The gage length is immaterial as far as the determination of this quality is concerned.

Kenyon and Burns¹² describe a new extensometer, wedge type, designed to draw accurate curves so that uniform and total elongation may be measured from the curve. Measurements of elongation may also be made in the area of the yield point phenomena. They describe test practice and a number of typical curves are reproduced. When due to cold work, the yield point becomes indefinite, it is considered to be the stress corresponding to an elongation increase of 0.5% of the gage length, determined by measurement from the stress strain curve. (On machines

not equipped with recording devices this point may be determined with any accurate extensometer.) The upper yield point is defined as the stress at which yielding begins; the lower yield point is the smallest value of stress to which the load sinks during stretching, or the smallest load under which stretching proceeds. A special celluloid scale, designed for measuring these values is described.

Two requirements for any test, according to Eksergian¹³ are: "(1) That the conditions of test duplicate those which actually exist—or that a relation between the two may be established, and (2) that the test contains sufficient information in a form which may be comprehensively interpreted. The simple tensile test, although somewhat lacking in the first requirement, fulfills the latter quite well. The general extension denotes the extent to which the material will behave uniformly while the local extension designates the ultimate capacity of the weakest section. These values should be considered with respect to the type of draw when correlating results."

Under definite testing conditions, the tensile test results are reproducible in any laboratory. The work of standardizing this test has covered a considerable period of time and many of the questionable points have been cleared up. For mill production testing of drawing quality material during processing and at the time of shipment, the tensile test is usually too time consuming. Consequently the simple tests, such as the Rockwell hardness and the Olsen or Erichsen cup draw tests, are used for this purpose. Mills are generally able to establish a correlation between the Rockwell and Olsen tests with actual performance records and feel that the two tests, properly considered are indicative of drawing quality, but are not a guarantee of performance because of the numerous drawing hazards external to steel quality. If a similar number of tensile tests were made, they would undoubtedly establish some relationship. The test is standard on plate and other materials having a strength requirement specification.

Hardness Testing—The useful hardness range on cold strip and sheets is roughly B-35 to B-100 Rockwell. When properly made, the Rockwell test on sheet and strip is consistent, reliable, and an effective measure of hardness. There are certain precautions necessary to obtain accurate results, and these are discussed in the article in this Handbook on the Rockwell Test.

Ductility Tests—The tests most commonly used to determine ductility are the Erichsen and Olsen cup tests, and to a certain extent, they give similar values. The Erichsen machine measures the gage and depth of cup in millimeters, while the Olsen test measures the same values in thousandths of an inch. The impression or draw of the Erichsen test is made with a cone shaped, spherical end plunger, while that of the Olsen test is made with a steel ball. It has been found by making a number of check tests that when the Erichsen result in millimeters is converted to inches, the actual value in thousandths is 10-14% higher than the Olsen test. Converting results on this basis will give comparative figures. However, this holds true for groups of samples, rather than for individual tests.

These two tests have never been standardized; consequently there is no generally accepted method of making either test, but the practice here described, if followed consistently, is probably as satisfactory as any. Briefly, cut the sample as wide as the machine will conveniently handle, oil the side in contact with the ball or plunger, tighten the die as snug as possible without jamming the screw, and then make the test. The "end point" of the Erichsen test is when, by observation, the break will just admit light; that of the Olsen test is when the needle of the pressure system begins to drop back. Variables in making the test are: Strip too narrow, giving high results; not breaking the cup, or breaking it too much; speed of testing; die tightness; lubrication and surface of sheet or strip. The most common error is to open the break too wide.

As these tests have never been standardized, there are many who doubt their actual value, while others believe that they are as good as any other test, provided a good practice is worked out and then adhered to rigidly.

Watson¹⁴ stated that a correlation between laboratory ductility tests and plant usage might be worked out in one plant, but the same correlation would not necessarily hold good for another plant.

Gillett's¹⁵ opinion is, that making tensile tests in both directions and measuring the elongation in several gage lengths is rather time-consuming, and for this reason the cupping tests such as are made on the Erichsen, Olsen, Guillery, and Wasau testers are generally used for ductility measurements, often with measurements of the load required. The cupping test has obvious advantages in that it tests the sheet in all directions, it gives a deformation somewhat analogous to that of deep stamping and does it without introducing press variables such as die clearance. Gil-

lett gives a number of references expressing different opinions of the reliability of cupping tests and the actual properties determined by them.

It may not be possible to get an extremely close agreement between individual machines on single sheet samples, but groups of samples average fairly close. There is a noticeable spread on individual results. However, results on the same machine, by the same operator or groups of operators, using the same practice, will be fairly consistent over a period of time.

The examination of the cup after the test is completed gives additional valuable information. The surface near the break gives an indication of the grain size; the position of the break gives an idea of the amount of cold work the material has received after the anneal; and the shape of the break indicates the thoroughness of the anneal and the directional properties present. The ratio of pressure at 0.250 in. draw and the maximum pressure during the test are also of some significance.

The bend test, as outlined in Table I, is useful on the harder tempers but is not of great value on the deep drawing grades. Some make a practice of opening the bend after the test has been made and examining the inside of the bend for additional information. Others have found the reverse bend test, made according to a definite practice, to be informative; the number of the reverse bends that the material will withstand before failure is considered an index of its ductility.

Microscopic Examination—The microstructure of the metal is most important in the deep and extra deep drawing grades. Usually the samples are taken parallel to the rolling direction but it is often desirable to examine the structure in both directions. The samples can be bolted together or mounted in bakelite, so that the cross section may be polished and examined. It is good practice to take all pictures at X100, X500, or X1000 so that the results may be compared from time to time.

The grain size of the material is controlled within close limits by controlling the processing. The grain size is important; for some work it must be fairly large, on other jobs it must be small or "in between." The permissible grain size depends somewhat on the type and depth of draw. The shape of the grains appears to be important, and the condition and distribution of the carbides should be observed and noted.

All steels have inclusions or sonims. Whether these are harmful or not depends on the number, size, type, and distribution in the material.

While there are limits to the desirable ranges of grain size, these limits are not clearly defined to the extent that these sizes apply to all jobs. What may be desirable in one case may not be good in another; but the requirements for any part have a certain degree of latitude. Usually the grain size will vary somewhat from surface to midthickness due to segregation. The degree depends on the severity of the segregation, and in well made steel this difference is negligible. On a straight rolled material there will be some difference in grain size from edge to center, and the same differences will be found from end to center on sheets cross rolled from sheet bars. Any irregularity in normalizing, and the usual temperature differences within the annealing box are reflected by slight differences in grain size. These are normal and expected differences which cannot be entirely eliminated, and affect the drawing quality only when they are severe and abnormally large.

Large variations in grain size within a given lot are detrimental as differences in the hardness and flow of the metal in the dies must be compensated for by changing the draw ring or hold down adjustment. The smaller grained material must be held more tightly to pull out the buckles or wrinkles, while the same adjustment would probably break a larger grained sheet or strip. For this reason, it is inadvisable to try to work both large and small grained materials with the same adjustment.

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Heating Steel Bars for Forging*

General—The details to be observed in the practice of heating and forging steel depend to some extent on the type and size of forging, method of forging, composition of the steel, and the subsequent disposition of the forging. The following suggestions are based on normal good practice for the production of steel forgings from bars and billets, up to and including 4 in. sq. or in dia.

There are six major metallurgical factors which should be considered in the heating and forging of the steel. These factors are:

- (1) Rate of heating to forging temperature;
- (2) Overheating and burning of the steel;
- (3) Forging temperatures;
- (4) Decarburization of the surface;
- (5) Scaling;
- (6) Finishing forging temperature.

Rate of Heating to Forging Temperatures—The time of heating should be just sufficient to bring the center of the bar or billet to the forging temperature. In general, for plain carbon steel of 0.50% carbon and less, a minimum time of 5 min. per in. of dia. or thickness is sufficient for heating bars up to 3 in. Although this is common practice, some metallurgists consider a slower heating rate more desirable. Bars over 3 in. in dia. or thickness require a slower heating rate. For steels having higher carbon content than 0.50%, somewhat slower rates of heating should be used. With some steels, even preheating should be employed in order to avoid rupturing when forced heating is applied. It is advisable with larger sizes or irregular shapes to determine the heating rate by imbedded thermocouples for the particular furnace and bar to be forged. To utilize the minimum rate of heating, it is necessary that the bars in the heating furnace do not touch, and that the furnace is of sufficient capacity.

Overheating and Burning—Overheating may be produced in the forgings by heating to such a high forging temperature that the grains in the steel become excessively large. This large grain size results in impaired physical properties of the metal unless the grain is refined by proper mechanical or thermal treatment.

The term "burning" as applied to steel is somewhat misleading, because the chemical reaction of the steel with oxygen is not necessary to produce the so-called "burning." This is evident since steel may be burned entirely on the inside, but may appear quite satisfactory on the surface. Burning of steel entirely on the inside is usually due either to decarburization on the surface or to an inside temperature which is much hotter than the surface at the time of forging. However, the presence of turbulent, free oxygen in the atmosphere surrounding the steel will usually cause the steel to burn at a much lower temperature than when no free oxygen is present.

Burning is an extremely overheated condition which causes the more fusible constituents of the steel to melt and run out into the grain boundaries and leave voids between the grains. Burning may occur in the heating furnace before any forging is done on the steel.

Direct impingement of the flame against the steel, especially if of an oxidizing nature, is likely to produce spot burning or overheating, and should, therefore, be avoided. Likewise, impingement of a jet of air against the steel is to be avoided in the heating furnace. Air may be used to blow the scale off the steel during the forging operation, provided the forging temperature of 2400°F. is not exceeded.

Forging Temperature—The safe forging temperature to be employed for steels depends on the composition of the steel, the furnace atmosphere, the temperature measuring equipment, the furnace equipment, and the type of forging operation.

In general, for either plain carbon or alloy steels, the forging temperature is lowered as the carbon content of the steel is increased. The effect of the various alloying elements on the forging temperature must be considered in relation to the quantity used and the other elements combined with them.

The flow of steel or its plasticity at the forging temperature depends upon the composition of the steel and the forging temperature. The higher the forging

*This article was prepared by the Subcommittee on Forging. The membership of the subcommittee was as follows: W. E. Jominy, Chairman; H. M. Spears, and A. M. Steever.

temperature, the greater the plasticity with resultant lower operating costs, but the finishing temperature is then generally higher, producing coarser grains. With higher forging temperatures, the steel is heated closer to the overheating and burning range and, consequently, good furnace equipment and accurate temperature measuring devices are necessary to avoid the danger of burning.

If optical or radiation pyrometers are used, it should be remembered that smoke, the reflection of incandescent flames or furnace walls, the distance from the hot object, the presence of scale, and the lack of black body conditions appreciably affect the accuracy of the reading. It is possible to correct for lack of black body conditions and the presence of scale, but much smoke or reflection from flames may make the readings valueless. On the other hand, if conditions can be made ideal, very accurate readings are obtainable with the optical pyrometer. If platinum-rhodium thermocouples are used, care should be exercised to be certain that the temperature of the thermocouple corresponds to that of the steel. Frequent checks of the accuracy of the platinum thermocouple are necessary since the wire is very easily carburized by carbon gases and is often contaminated by iron and silicon.

Decarburization—Practically nothing is known about the rate of decarburization in different atmospheres at forging temperatures above 2000°F. It is probably safe to assume that increasing the heating time will increase the depth of decarburization. All precautions should be taken to avoid decarburization, so that the forgings can respond to heat treatment and thereby produce the physical properties expected.

Scaling—Scaling is the cause of more forging difficulties than is usually realized. Scale ruins most refractories; it is often hammered into the surface of the forging, causing machining difficulties and weak spots; and sometimes causes sticking in the forging dies. Scale represents an economic loss of metal and loss of time in removing it. It is desirable to have as little scale as possible, so a minimum time of heating should be employed. The presence of free oxygen in the furnace atmosphere causes a decided increase in scaling. If the presence of free oxygen in the furnace atmosphere is avoided, little is gained in reduction of scale by having more than a moderate excess of carbon monoxide. It has been found that in a gas fired furnace, using ordinary city gas, practically the same amount of scale is formed when the atmosphere contains 8.0% carbon monoxide as when 0.5% carbon monoxide is present, and that it is necessary to exceed 12% of carbon monoxide before a marked reduction in scaling is produced. This applies also to oil fired or butane fired furnaces, provided no free oxygen is present. The rate of scaling is also increased rapidly with an increase of heating temperature.

The Finishing Forging Temperature—In drop forge work, the finishing temperature is usually well above the critical range of the steel and practically no strength is imparted to the steel by the mechanical work of forging, although a certain amount of grain refinement results. In many drop forge operations, the finishing temperature is so high that large grains remain in the forging. Consequently, for best quality forgings, it is advisable to normalize in order to obtain a uniform, well refined grain structure. In addition, normalizing usually makes the steel more easily machinable, relieves the forging and cooling strains, and produces a more refined grain structure, especially if the finishing temperature was comparatively high. The normalizing temperature selected should be sufficiently above the critical range to completely eliminate any coarse structure that may be present.

Cooling After Forging—After the forging operation, it may be desirable because of the shape or composition of the steel (usually high carbon) to retard the cooling rate of the forgings. To retard the cooling, the forgings may be placed in a more or less protected enclosure, in ashes or lime, or they may be placed in a hot furnace.

Forging Furnace—Because of the greater ease of temperature control, better control of the induced air, better control of the time cycle for heating the bars or billets, and better fuel efficiency, a continuous type of forging furnace equipped with pyrometers is recommended wherever possible.

Care should be taken to avoid the accumulation of oxide slag on the floor of the furnace, since the presence of such slag causes pitting of the bars or billets which come in contact with it. In oil fired furnaces there is often an accumulation of coke at or near the burners, and occasionally other places. This coke or carbonaceous material, if not removed, may fall on the bars and billets, carburizing

them at the point of contact and causing hard spots, and sometimes causing melting and pitting.

Rate of Heating Carbon Steel Bars for Forging—Plain carbon steel of 0.50% carbon and less, in sizes up to 3 in. sq., may be heated at the maximum rate of 5 min. per in. of dia. or thickness. Although this is common practice, some metallurgists consider a slower rate more desirable. For steel having higher carbon content than 0.50%, somewhat slower rates of heating should be used in order to avoid rupturing from too rapid heating. The rate of heating to be used will depend on the size of the bar and its composition. In general, bars of 1% carbon and over and 1 in. in dia. or over should be preheated to 1300-1400°F. before placing in the forging furnace.

Forging Temperature—The following table gives the maximum temperatures recommended for forging plain carbon steels of the carbon contents listed:

Carbon Steels to be Forged % Carbon	Max. Forging Temp. °F.
0.10	2400
0.30	2350
0.50	2300
0.70	2225
0.90	2150
1.10	2075
1.50	1900

Heating Alloy Bars for Forging—This recommendation is to cover the heating of alloy steels having a carbon content up to 0.60% and a composition corresponding to any of the following S.A.E. series: S.A.E. 2300, 3100, 3200, 3300, 3400, 4100, 4600, 5100, and 6100.

Heating Rate—Bars or billets of 0.50% carbon or less may be heated at the maximum rate of 6 min. per in. dia. This applies to sections of 3 in. dia. or smaller. For larger bars or higher carbon content steels a slower rate of heating is recommended to avoid rupturing from too rapid heating.

Forging Temperature—The following table gives the maximum temperatures recommended for forging the above listed alloy steels of the carbon contents as indicated:

Carbon %	Max. Forging Temp., °F.	Carbon %	Max. Forging Temp., °F.
0.10	2350	0.40	2250
0.20	2300	0.50	2200
0.30	2250	0.60	2200

Precautions—In addition to the recommendations on pages 663-665 attention is called to the following precautions:

- (1) It is suggested that the finish forging temperature be not lower than 1800°F.
- (2) Scale is more adherent in the chromium and nickel containing steels and additional precautions to minimize the scale formation should be taken. This can be done by:
 - (a) Making sure that no free oxygen is present in the heating furnace atmosphere.
 - (b) Reducing the temperature at which forging is carried out.
 - (c) Preheating the bars to not over 1400°F. and permitting them to be at the high temperature for a minimum of time. This is usually done with the larger sections only.
- (3) With larger forgings, slow cooling from the forging heat is advisable to avoid internal ruptures. When the section of the forging exceeds 3 in. in dia. for more than 6 in. of length, cooling should be slower than natural air cooling.

Large Forgings

By John L. Cox*

General—The two main reasons for forging steel are to reduce the block of metal to approximately the dimensions of the finished article, and to complete the work of refining the coarse grain of the steel ingot, which for alpha steels was started by the high heat required for forging. Secondary objects of forging are so to orientate the unavoidable inclusions in the metal that they will have the minimum injurious effect, and to increase the physical properties of austenitic steels.

Both temperature and time are necessary for the first refining action. Ordinarily the initial heat should be as high as is prudent for the composition, and for alpha steels should be thoroughly soaked through the mass. Subsequent reheatings may be lower in temperature, but the steel should be thoroughly soaked. Austenitic steels are preferably soaked out at a moderate heat, brought quickly to the forging temperature throughout, and at once forged. In general, forging preferably should continue until the metal is too cool to permit ready grain growth, which in most cases is approximately when the surface of the forging shows polished die marks, or when breaking scale has ceased to form.

Ingot for Forging—Ingots must be of the proper chemical composition and should be of a dead-melted steel. They may be of any advantageous shape that will permit satisfactory solidification. For solid forgings it is highly important that the part of the ingot entering the forging be free from secondary, as well as primary shrinkage, especially when cuts occur across the ingot axis, as in crankshafts. In general this solidity can be obtained only by using ingots cast big end up and fed by a refractory-lined sink-head of ample proportions, unless very excessive top scrap is to be cut.

Complete freedom from central shrinkage is not so important in ingots for hollow forgings, especially in cases where the ingot is bored cold or trephined hot by a hollow punch, but it is always desirable.

The cross section of the ingot should be such as will permit finishing under proper conditions after heating, with a reasonable amount of reduction to insure thorough working throughout the section to be used so as to cause complete destruction of the ingot crystallization. Excessive reductions are not in themselves beneficial to good steel. They are injurious to pressure cylinders when forged solid and bored out, or even when forged hollow unless made by expansion of the diameter of a thicker walled cylinder, and may be expected to produce low extensions in tangential test bars taken in a transverse plane. The larger it is the more slowly an ingot cools; consequently, the coarser is its crystallization, the more pronounced the segregation, and the more serious the internal defects are likely to be. There is then little or nothing gained by giving more pronounced orientation to more numerous and larger inclusions, or by putting more work into breaking up a worse initial structure, with always the risk of the defects remaining.

Excluding forgings with large collars, a reduction of 3:1 should answer for nearly all work stressed and tested longitudinally, while a reduction of 2:1 should suffice for hollow work stressed and tested transversely.

For forgings with large collars there must be greater dependence on the heat refinement, but a reduction of about 1½:1 should be allowed on the collars. It is bad practice to round up an ingot that will barely yield the collar diameter.

To avoid excessive liquation and the coarse crystallization of slow cooling, it is advisable that ingots for forgings be cast in iron molds with heavy chill walls. Further, the metal cooling in basaltic columns from chill mold walls is cleaner and stronger than the interior metal of miscellaneous crystals. Wherever possible, such metal should be conserved for the more highly stressed parts of the forging. If of a size and of a composition making the step safe, an ingot may be allowed to go cold after casting. Conditions will dictate whether cooling be freely or at a restricted rate, or only after annealing. If very large, it is preferable to charge the ingot into the forge furnace while still hot, to avoid waste of heat and the risks of cracking during cooling and reheating.

Heating—Heating should be done with a soft, noncutting flame to avoid excessive loss by scaling and the risk of burning the metal. Ample time must be allowed

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for bringing the ingot to forging temperature if internal fire-cracks or "clinks" are to be avoided, which are formed when the nonplastic center of the ingot is ruptured transversely by the pull of the expanded surface metal. The time to heat is an increasing function of the size of the ingot, depending, too, upon its initial temperature.

When plain, medium carbon steel ingots of 40 in. in dia. are charged cold, safe practice represents heating about 1 hr. to the in., with a soaking time of $\frac{1}{4}$ hr. to the in. after reaching heat. Alloy steels have much lower coefficients of conductivity, so require proportionately longer time to heat.

For best physical results ingots of austenitic steels should be thoroughly soaked at approximately 1700°F., brought quickly to the forging temperature throughout, and forged without the usual soaking. However, the surfaces are likely to be torn. Better surfaces and more plastic material for forging will follow a heating more nearly of the type usual for alpha steels.

Forging—The forging tool may be a steam hammer or a hydraulic press, with sufficient power to work the metal thoroughly. The slow movement of a press tends to work large masses more deeply, and although the maximum pressure is limited it can be exerted at any point of the stroke. There is no theoretical limit to the pressure produced by a hammer, but the power of the tool decreases rapidly with restriction of the stroke and must be proportional to the work if more is to be done than move the surface metal. Forging should start by comparatively slight reductions on every face to consolidate the ingot structure, followed by the heavy reductions of the main roughing step. The preliminary consolidation is of especial use before spreading an ingot lengthwise of the dies, as it tends to prevent tears in the surface.

The metal must be worked throughout to weld any clean-walled internal openings that may exist and to refine the grain, as well as to avoid transverse fracture of the center, and to avoid mechanical piping of the bottom of the ingot by drawing the surface metal over the end. Enough reduction should be left for the finishing step to insure work being continued until the piece has fallen to a temperature too low for any considerable grain growth to occur.

Since the orientation of inclusions profoundly affects the stretch and contraction of the steel in which they occur, it is important to cause flow of the metal in the direction of the stresses to be borne. For this reason upsetting, or expanding on the horn or expanding mandrel, at some step in the forging operation greatly improves transverse tests.

When making set-downs with V tools, care must be exercised that the tools be not sunk too deeply to allow good reduction by forging below the bottom of the cut, either by radius tools or the rounded edge of the die, for the V tool cuts and stretches but does not forge. A V tool sunk deeply in metal not quite hot is very apt to produce a cavity in the metal below it.

It is important that sufficient metal be left between set-downs, especially in the case of collared shafts, to produce the intermediate final length required with a minimum cut on the inner faces of the collars. Excess metal may be turned off the shaft, but shortage of metal requiring part of the collar to be turned to the shaft diameter is very bad practice, as it puts into the highly stressed part of the shaft metal which has had only the reduction of the slightly stressed collar.

Long forgings of large diameter or of sensitive composition must often be kept hot (by auxiliary heating means outside the forge furnace) throughout those finished portions which would otherwise cool too quickly.

Sufficient top scrap must be cut to remove all trace of central ingot shrinkage that would be injurious in the finished article, and as much more as the specifications require. Sufficient bottom scrap should be cut to remove all casting surface defects, and if transverse tests be required from an unexpanded forging it is wise to cut considerably more.

Annealing—Except for the softest materials, carefully finished, it is of advantage—and in the case of solid forgings of large dimensions or forgings of high carbon or hardenable alloy steels it may be imperative—to anneal or otherwise slowly cool after forging is completed. It is well to check cooling before the temperature has reached about 600°F. if flakes and internal or external cracks are surely to be avoided.

If only part of a sensitive ingot has been used and the balance is to be reserved for future use it should be annealed, or buried in ashes, to avoid cracking.

If a large forging has only been buried in ashes from the forge, it must be regularly annealed to free it from stresses and refine its grain.

Annealing substitutes the grain size of its temperature and time for that existing in the piece as it left the die. If finishing be done at a high temperature it will require a higher heat to refine the existing grain than if the finishing had been done at a more suitable heat, and the resulting structure may require one or more further annealings at successively lower temperatures to produce the best annealed structure of which the piece is capable. Very large pieces often require the repetition of a particular annealing step before the full effects of its temperature have been obtained. This is better practice than to lengthen unduly the time at that temperature.

Forgings of austenitic steel, being always in the original phase with no volume changes occurring at passage through a critical temperature, are comparatively free from stresses and strains. They need only be heated sufficiently to relieve the stresses due to unequal rates of cooling.

Treatment—When higher physical properties are required than are obtainable from a forging in the annealed state an increase may usually be obtained by normalizing, or by quenching and tempering.

Normalizing consists in heating the piece to a temperature somewhat above that at which the metal is in the gamma phase, holding it there for a time sufficient for homogenization to occur and then cooling it freely in the open air. Depending upon the size, character and chemical composition of a forging, this step may not, or should, be followed by a tempering at a heat well below the critical range. The result is usually a moderate increase in tensile strength, a considerable increase in elastic limit, with a small loss in ductility.

When still higher properties are required and the character of the forging permits it, the highest attainable figures are reached by a heating such as described for normalizing, followed by a quench in a liquid medium, usually oil or water, followed by the tempering.

It is usually considered unsafe to apply this drastic treatment to solid forgings of any considerable diameter; it is rarely given to pieces over about 8 or 10 in. diameter or having walls over 8 in. in thickness, but under proper conditions it can be used on those much larger.

Austenitic steel forgings in general can only be softened by heat treatment. Balanced high physical properties must be obtained by work done cold or at comparatively low temperatures; for while some increase in tensile strength can often be gained by reheating forgings, with carbides in solution, to a temperature at which the carbides will precipitate, there is usually a disproportionate increase in brittleness and a probable loss in corrosion resistance.

Internal Inspection—Exposed defects on the surface of a forging are easily examined and their seriousness evaluated, but hidden defects may be as serious as unexpected. For this reason, it is always advisable to bore an axial hole through every major forging when such a step is possible. The hole should be as large as the necessary residual strength of the forging will permit. The larger the ingot from which the forging was taken the larger, if possible, should be the axial hole. Such a hole permits an examination of the interior of the forging by means of a bore searcher and will disclose the presence of shrinkage cavities and transverse fissures the existence of which otherwise would be wholly unsuspected. Slight defects, if present, may frequently be ground or machined out without undue loss of strength, but transverse cracks are sufficient cause for condemnation.

Not only does this axial exploration hole allow closer inspection, but it helps to reduce the stresses imposed both in heating for treatment and the subsequent cooling. Its importance is greatest when a liquid quenching step is involved, and it is practically indispensable in the quenching of large forgings, by allowing access of the cooling medium to the interior of the piece.

In all cases sharp re-entrant angles in any of the steps of manufacture or on the finished product should be avoided, as they form starting points for failure in treatment and service. The most liberal fillets compatible with the design should be allowed. Too small fillets may be a source of trouble in manufacturing operations as well as in service.

Fabricating and Finishing the Stainless Steels

By V. W. Whitmer*

The forging operations are not covered in this article as they are discussed in the article on the Forging of Stainless Steels on page 841 of this Handbook.

Types—The use of stainless steels in various industries is today quite large and varied. There are many types available to meet specific conditions insofar as analysis is concerned, but nearly all of them can be grouped in two general classes, from a fabricating standpoint. The first class, containing chromium as an alloying element, with varying amounts of carbon for heat treating purposes, is generally known as the straight chromium or ferritic type. The second class, containing both chromium and nickel, with low carbon, does not respond to heat treating for hardening. It is known as the chromium-nickel or austenitic group.

Excluding the higher carbon alloys in the straight chromium group, the two most commonly used alloys in these groups are probably those containing 18% chromium with low carbon, and the 18% chromium and 8% nickel. In both groups there are numerous others containing higher percentages of alloying elements, chiefly for heat resistance, but they are worked much the same as these two. Hence, in this article only the two alloys mentioned will be considered with additional notes when necessary.

Hot Working Operations

Piercing 18% Chromium Steel—For piercing, heat the same as for forging. A higher temperature will generally prove satisfactory. While the 18% chromium has been the most commonly used in the group the higher chromiums of 23 and 28% have been pierced successfully.

Piercing 18-8 Alloys—For piercing heat the same as for forging the 18-8 alloy, but to a higher temperature. The 18-8 alloy is the most commonly used in the chromium-nickel group. The higher alloys such as 25-12 and 25-20 have also been pierced successfully, the latter offering considerable difficulty.

Welding 18% Chromium Stainless—This alloy can be welded by any commercial method except forge or fire welding. Tight, solid welds are produced, insofar as fusion and porosity are concerned. A base wire of the same analysis as the steel is used with a slightly reducing flame for gas welding. For arc welding use a coated electrode which will protect the metal going through the arc from oxidation by the air. It will also cover the deposited bead with a slag blanket which stays molten to prevent loss of any chromium by oxidation. Because of the high temperature employed in welding a large grain will be developed, resulting in a brittle weld. At elevated temperatures such as 400°F. and higher some toughness is present. However, the 18% chromium is not recommended for welding, because it does not respond satisfactorily to subsequent heat treatment. If the chromium should be 15-16%, it is possible to anneal after welding and produce good ductility and bending properties.

The higher chromiums behave in a similar manner, but the lower type, around 12% chromium, is capable of heat treatment and can be annealed to show some ductility after welding. Recent work has shown that additions of columbium, titanium or aluminum will reduce air hardening in the 12% chromium alloys. Such additions to the electrodes do not produce soft ductile weld metal and hence, if the welds are to be placed in service as welded—an austenitic electrode such as 18-8, 25-12 or 25-20 should be used, depending upon the application. Such welds will be tough and ductile but will have a higher coefficient of expansion on heating and cooling than the straight chromium alloy. Nevertheless, welding is not frequently employed on these alloys.

Welding 18-8 Alloys—The chromium-nickel stainless steels are well adapted to welding and like the others can be welded by any commercial method except fire. Fire welding is not successful, as a refractory film of oxide forms on the surface of the material at the welding heat which will not dissolve or fuse with the commercial fluxes used today. This film acts as a separator, when the pressure is applied on the two sections, and prevents adhesion.

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In gas welding a rod of the same composition should be used with a slightly reducing flame, having about $1/32$ in. of acetylene feather on the end of the inner blue cone to prevent any possible oxidation of the chromium. If more acetylene is used the weld may become carburized, and with less the chromium may be burnt out. It is also advisable to apply a water paste of a good stainless flux to the bottom side of the joint to protect this side from contact with the air.

The 18-8 alloy has a high coefficient of expansion, about 60% more than common steel, and it is therefore necessary to hold the work in some manner while welding to prevent the edges from moving away from each other. Because of the greater expansion, the joint should be so held as to produce as little buckling as possible when cooling. Gas welding is used chiefly on 16 gage and lighter sections, although it can be satisfactorily used on heavier sheets.

Electric arc welding is probably the most common method used on stainless steel. A heavy flux coated electrode of the same analysis is necessary. This flux protects the molten metal, both while going through the arc and after being deposited, from oxidation by the air. It should not contain any material which would raise the carbon content of the weld metal, as this would reduce the ductility as well as the corrosion resistance. Use reverse polarity, that is, the electrode is positive and the work is negative. The 18-8 alloy has a lower melting point than steel, as well as a lower heat conductivity; therefore, less heat can be used and good penetration will be obtained in comparison with mild steel. A heavy bead or series of heavy beads should not be deposited at one time, as the excessive contraction will cause cracks. Deposit light beads about $1/8$ in. or less in thickness. All 18-8 welds properly made will bend flat back on themselves in either direction on $1/8$ in. plate without cracking.

Occasionally, columbium or titanium additions are made to 18-8 S to prevent carbide precipitation. This is not necessary with low carbon in light plates but is desirable in thickness over $1/2$ in. or where the equipment will operate in the carbide precipitation range of 1000-1500°F. and under corrosive influences. Titanium, in the welding electrode, is not advantageous, as it is nearly all lost during welding. Columbium is more efficient and will be reduced to a less extent.

Spot, seam, and flash welding are satisfactory on 18-8, but because of the characteristics of the alloy a closer adjustment between current time and upset are important. Automatic control is highly advisable with these products. Less total heat will be required than with the same sections of common steel.

The same procedure as with 18-8 should be employed in welding the higher chromium-nickel alloys. As these alloys are usually subjected to high temperatures, the weld metal as well as the plate or body must withstand the same service.

Cold Forming Operations

Cold Rolling 18% Chromium Stainless—The straight chromium alloys can be cold rolled in sheet or strip or drawn into wire similar to steel, except that lighter drafts, less speed, and greater pressure are required. High finish surfaces can be obtained on cold rolled strip. Very little polishing is required on an article made from this product. The hardness on cold working will increase to about 187-241 Brinell (95-100 Rockwell B) but will seldom exceed this range. Annealing will reduce these values to about 140-160 Brinell (80-85 Rockwell B).

Cold Rolling 18-8 Stainless—The chromium-nickel alloys can be cold rolled into strip or drawn into wire by methods similar to those employed for the straight chromiums, and will yield high finished surfaces, but considerable hardening will result. Cold working will raise the hardness up to about 400 Brinell (40-44 Rockwell C), with as high as 250,000-300,000 lb. tensile strength.

Drawing 18% Chromium Stainless—This alloy has about two-thirds as much ductility as ordinary deep drawing steel. In stamping, the draw should therefore be generally less for each operation. It is frequently possible to take two or more reductions without annealing under certain conditions, although, it is generally advisable to anneal after each operation. Annealing should be done at 1450°F., followed by air cooling. A good drawing lubricant is necessary in order to adhere to the work in the presence of greater pressure than required for ordinary steel. Good adhesion and lubrication should be stressed rather than a heavy base. In the straight chromium group, the alloys containing over 23% chromium will not be as good from a drawing standpoint as the lower ranges.

Drawing 18-8 Stainless—Because of its high ductility, this alloy is extensively used in deep drawing work. It has a much higher elongation as measured by a tensile test than extra deep drawing steel, showing about 45-50% as compared to 25-30% elongation in 8 in. for steel. Likewise the Olsen and Erichsen test values are higher. It is subject, however, to rapid hardening on cold working; hence as much work as possible should be performed in one operation. It is difficult to produce deep draws without annealing between operations, although two light draws can frequently be made without annealing. This annealing consists of cooling rapidly from 1950°F. either in air or water.

Reduction of 30-35% can be made in the first operation, but subsequent reductions should be about 20%. If too much work is done at one time and the article permitted to stand too long before annealing, it is apt to crack from excessive cold work. For this reason, if more than 40% reduction is made the job should be annealed at once. The presence of a flange will reduce this tendency considerably. About 2-2½ times as much clearance should be allowed as for steel or brass.

Because of the high physical properties and stiffness of the 18-8 alloy, one-third more power will be required to produce a given draw. A lubricant with high adhesive qualities capable of withstanding the high pressure without squeezing is quite necessary. All lubricants should be completely removed before annealing, as it will very likely injure the metal surface if left on during the annealing operation. The dies, for production work, should be hard, bronze inserts for the rings and either bronze, steel or cast iron for the punch. The ring should be kept well polished, if possible, in the direction of drawing. Proper choice of lubricant should assist in maintaining this polish to reduce scoring.

Spinning 18% Chromium Stainless—The straight chromium alloys, especially in high ranges of 17% chromium and over, have not been particularly successful in spinning operations. Reductions are less and more annealing is required than with the lower alloys. For best results with this type, the chromium should be about 12.0-17.0%.

Spinning 18-8 Stainless—The alloy 18-8 of spinning quality, having a high ductility in the annealed state is well adapted to spinning. Many articles have been spun from 18-8 where the number required or the variety of size and shape did not warrant making up dies for deep drawing.

In such cases, 18-8 can be spun, but it may be necessary to anneal, as required at certain stages. The ordinary tools or the roller type can be used. A chromium-nickel cast iron or oil hardened steel roller works well because of its ability to hold the lubricant. A heavy body grease or soap must be employed, keeping the surface well covered to prevent scoring or abrading. Do not attempt to do too much work before annealing, as cracks are apt to develop. Maintaining a flange while spinning has been found to be of value in reducing breakage.

Soldering 18 and 18-8 Chromium Steels—Both types of stainless steels are soldered readily, as the analysis has no bearing on the strength of the finished joint. If pickled sheets are employed, the ordinary zinc chloride or cut acid with commercial half and half solder will give fair results. However, stronger joints will be produced if the special stainless steel soldering fluxes are used, several of which are on the market. If the steel is polished, the edges should be roughened with a coarse file or emery cloth to obtain adhesion. Use a large soldering iron with as low a temperature as possible to keep buckling to a minimum. When the joint is completed it should be washed with about a 5% soda solution. Washing will neutralize any remaining acid which, if not removed, will corrode the metal. If the joint is of such a nature that washing on both sides is impossible, it should first be tinned with a strong flux and washed, then assembled and finish soldered with a flux that is as near neutral as possible, so that if it is not removed, it will not seriously corrode.

Machining 18% Chromium Stainless—This alloy machines a little differently than ordinary steel and more nearly resembles a 0.40-0.50 carbon steel. For best results it should be in the cold drawn or cold drawn and annealed condition. The same applies to sheet or strip either cold rolled and annealed or just annealed.

The 12% chromium containing higher sulphur along with various other elements is recommended for machine work. On a basis of 100% for screw stock the product will rate about 90% or better. It is used on automatic screw machines along with regular screw stock.

Machining 18-8 Stainless—This product is tough and difficult to machine. Best results are obtained with a slow cutting speed and moderately heavy cuts. Tools must be kept sharp and cutting, as any dragging will tend to work harden the product and will further increase the difficulty. Drills should be ground flatter than usual to produce less wedge effect and the speed reduced to about one-half that used for drilling steel. Center punch marks should be as small as possible to reduce the effect of cold working.

For drilling or cutting a good grade of sulphur base oil should be used. In sawing, a high speed blade should be used of the fine tooth, wavy type. A circular saw is preferred whenever possible.

Selenium additions to 18-8 will sharply increase its machining properties, but at the sacrifice of some corrosion resistance. This is generally not serious and the greater ease of machining more than warrants the slight loss in corrosion properties.

Pickling—Both the chromium and the chromium-nickel groups form an oxide when annealed in a reducing atmosphere which is practically impossible to remove by pickling. When a neutral condition is maintained, the sheet can be pickled in a solution of 10% (by weight) muriatic acid, that is, half and half commercial acid at about 130-150°F. or a mixture of 6-8% sulphuric acid with 2-4% muriatic at 150-170°F. The former is preferred, but is more expensive. After about 20 min. in this solution the section should be removed, dipped in cold water before any acid dries, then scrubbed and immersed in a 20% solution of nitric acid, either warm or cold. This operation will produce a clean white sheet which should then be washed in water and dried.

Polishing and Buffing—Both types of stainless steel if only rough ground with a coarse wheel, will discolor if subjected to a salt spray. However, if a higher finish is applied, no rusting will occur on the 18% or higher chromium steels or on any of the chromium-nickel steels.

Rough grinding should be done with 80 grit, set up with glue and abrasive on a cotton wheel. This should be followed by 100 grit with the wheel surface greased, then with successive fine wheels, such as 120, 150, 180, 200, and 240, depending upon the finish desired. Grit up to 180 should be of the manufactured type, low in iron. From 180 up, Turkish emery will give best results, as fewer deep lines will be produced.

For a higher finish, go through the 240 grit with grease, then buff with a stainless steel buffing compound on a cotton buff and follow with a few passes using green chromium oxide grease stick for final color. Do not buff with chromium oxide, as drag pits are likely to develop.

For cutting, a speed of 5,000-6,000 f.p.m. should be used and for buffing 6,000-8,000 f.p.m.

The Forging of Stainless Steel

By Owen K. Parmiter*

General Instructions—The term "stainless steel" may refer to any one of 60 or more corrosion resistant steel compositions, each one possessing some special property or particular characteristic not found in the others. All stainless steels, however, have some properties in common which include "red hardness" or resistance to the softening effect of heat and a low degree of heat conductivity. These characteristics make forging somewhat difficult. Careful preheating and prolonged soaking are necessary in all cases and some special compositions require extremely narrow heating ranges.

Since it is impractical to outline specific forging instructions for each type of stainless steel, in this article, the field has been divided into three general groups to include, The Hardenable Types, The Chromium Irons, and The Austenitic Types. Only the most popular and representative steels in each general group are considered.

Hardenable Types (Semi-martensitic and martensitic chromium-iron steels)—The various compositions included in this group possess air hardening properties and also red hardness to a limited degree. This makes forging somewhat difficult because rather narrow heating ranges are necessary. For all forging operations, it is necessary to preheat the stock and soak for a considerable length of time in the vicinity of 1450°F., also to hold longer at the required heat than ordinary steel. Frequent reheating is advisable. After forging, these steels should be cooled slowly and evenly; then they are hard and must be annealed if machine work should be required.

In forging the higher carbon types of stainless steel (above 0.60% carbon), care must be taken not to overheat them, for as the carbon content increases, the initial forging temperature decreases. The structure of these steels has a tendency to become austenitic if overheated, and when such a condition is present, the steel does not respond well to hardening.

Forging temperature ranges for this group are as follows:

Type No.	Commonly known as	Typical Carbon	Composition, % Chromium	—Forging Temperatures—	
				Initial Heat, °F.	Finishing Heat, °F.
501	5% Chromium Iron (46)	0.10	5.00	1950-2000	1650-1700
403	Turbine Blading Type	0.12 Max	12.25	2000-2100	1450-1500
410	Chrome Iron	0.12 Max	13.50	2000-2100	1600-1700
416*	Free Machining Type	0.12 Max	13.00	2100-2200	1500-1600
420	Original Cutlery Type	0.35	13.00	1950-2050	1650-1700
440	Surgical Instrument Type	0.65	16.50	1950-2000	1700-1750
440	High Carbon Cutlery Type	0.85	17.00	1900-2000	1700-1750
440	Ball Bearing Type	1.05	18.00	1850-1950	1700-1750

*Free Machining—contains high sulphur or selenium.

Soft Types (Semi-ferritic and ferritic chromium-iron steels)—The nonhardening steels comprising this group are highly malleable and ductile. For all forging operations it is necessary to preheat the stock and thoroughly soak at about 1450°F. Forging should be fairly rapid at the initial temperature but should be more gradual as the metal cools. Unless there is considerable reduction to be done, the temperature should be held as low as is consistent with workability, and in no case should the finishing temperature exceed 1400°F. If these steels are overheated, a coarse structure results and much of their toughness and ductility is sacrificed. Good refinement of grain is possible by finishing at a low heat. Although they possess virtually no hardening properties, it is sometimes desirable to anneal after low temperature working to remove strains.

Forging temperature ranges are as follows:

*Metallurgical Eng., Firth-Sterling Co., McKeesport, Pa. Prepared for the Subcommittee on Forging. The membership of the subcommittee was as follows: Adam Steevey, Chairman, R. W. Thompson, F. B. Foley, O. W. Ellis, H. M. Spears, W. E. Jominy, W. W. Orley, and J. H. Friedman.

Type No.	Commonly known as	Typical Carbon	Composition, % Chromium	Forging Temperatures	
				Initial Heat, °F.	Finishing Heat, °F.
430	17% Chrome Iron	0.12 Max.	14.00-18.00	1900-2000	1350-1400
430F*	17% Chrome Iron Free Mach.	0.12 Max.	14.00-18.00	2000-2100	1350-1400
442	20% Chrome Iron	0.35 Max.	18.00-23.00	1900-2000	1300-1400
444	28% Chrome Iron	0.35 Max.	23.00-30.00	1900-2000	1300-1400

*Free machining—contains high sulphur or selenium.

Nonhardenable Types (Austenitic chromium-nickel-iron alloys)—The steels in this group possess varying degrees of strength and hardness at the high temperatures necessary for forging. All of them are more difficult to forge than ordinary steels and require more blows under the hammer to accomplish the same degree of reduction. Like all high chromium steels, their heat conductivity is low so it is necessary to soak them thoroughly at the preheating temperature of about 1500°F. The first hammer blows should be light. With the exceptions of Type 310 and Type 311 none of these austenitic stainless steels should be held for a prolonged period of time at the initial heat of forging. All of this group of steels should be finished at a comparatively high heat (1700-1800°F). At forging heats lower than about 1700°F, these steels are hardened by the comparatively cold working and have a tendency toward red shortness.

Specification for this grade of stainless steel formerly called for 0.20-0.70% manganese. Recent experience has shown better hot working properties when the manganese content is between 1.25 and 2%. This is particularly true in the austenitic stainless steels containing molybdenum, columbium, silicon, and titanium.

Forging temperature ranges are as follows:

Type No.	Commonly Known As	Typical Compositions, %				Forging Temperatures	
		Carbon	Chromium	Nickel	Other Alloys	Initial Heat, °F.	Finishing Heat, °F.
302	18-8	0.08-0.20	17.50-19.00	8.00-9.00		2100-2200	Above 1700
302B	18-8B	0.08-0.20	17.50-19.00	8.00-9.00	Si 2.00-3.00	2100-2150	" 1700
303	18-8 FM	0.20 Max.	17.50-19.00	8.00-9.00	S or Se 0.07 Min. Mo 0.60 Max.	2100-2200	" 1700
304	18-8S	0.08 Max.	17.50-19.00	8.00-9.00		2100-2200	" 1700
317	18-8-Mo	0.10 Max.	18.00-20.00	14.00 Max.	Mo 3.00-4.00	2100-2200	" 1800
321	18-8S-Ti	0.10 Max.	17.00-20.00	7.00-10.00	Ti Min 4XC	2150-2200	" 1700
347	18-8Ch	0.10 Max.	17.00-20.00	8.00-12.00	Cb 10XC	2150-2200	" 1800
325	8-22-Cu	0.25 Max.	7.00-10.00	19.00-23.00	Cu 1.00-1.50	2000-2050	" 1800
307	20-10	0.08-0.20	20.00-22.00	10.00-12.00		2100-2200	" 1800
309	25-12	0.20 Max.	22.00-26.00	12.00-14.00		2200-2300	" 1800
310	25-20	0.25 Max.	24.00-26.00	19.00-21.00		2100-2200	" 1800
311	20-25	0.25 Max.	19.00-21.00	24.00-26.00		2100-2150	" 1800

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Hot Mechanical Working of Steel*

Purpose of Hot Mechanical Working—Steel which is cast from the melting furnace into ingot molds must be reduced from the ingot by mechanical force through the intermediate stages of bloom and billet to bar, sheet, strip, coil, or forging, which are the common hot finished forms of steel. This mechanical force is applied to the steel while hot for several essential reasons.

The ingots into which the steel is cast from the melting furnace usually represent a considerable mass of metal which is slow to solidify and cool to room temperature; hence it has a very coarse crystalline structure. Material in this condition is deficient in ductility and very heavily strained. These strains are of sufficient magnitude to cause rupture of the mass if subjected to unequal or sudden temperature changes. To refine this structure is then one of the primary reasons for hot mechanical working of steel. By heating steel to its plastic state and mechanically working it, the coarse crystals of the cast ingot are rearranged, and the metal flows along desired lines. This results in a reduced section of greater homogeneity and refined crystal structure. By the proper selection of temperature and the application of mechanical work through rolls, dies, and the like, the physical properties of the forged steel may be increased over those of the original cast ingot both statically and dynamically.

Hot Working Range and Effects—Heating steel above a certain blue heat range of about 700°F. constantly decreases the strength and increases the plasticity until a temperature is reached where the lowest melting constituent of the steel starts to melt. At this particular temperature the strength is greatly decreased and the mass also loses plasticity and tends to crumble under applied stress. When this point is reached, mechanical work cannot be performed as the steel will crumble rather than flow.

The optimum hot working temperature is, therefore, a balance or average between decreasing strength and increasing plasticity. This temperature will vary with different compositions of steel and is covered by a range called the hot working range. The top of the range is limited by a margin of safety below the melting point of the lowest melting constituent, and the lower end by the temperature at which strength increases and plasticity decreases to the extent that excessive pressures are required to cause flow, thus limiting the efficiency of the process and possibly causing ruptures in the metal.

Finishing Temperatures—Although the final properties of the finished steel are usually determined by heat treatments applied subsequent to the hot mechanical working, the temperature at which the mechanical work is finished (so-called finishing temperature) is important in governing the final treatments necessary and the properties obtained. It is generally conceded that the lower the finishing temperature, the finer the structure of the mechanically worked piece and the more amenable it will be to simple heat treatments. The actual temperature is, however, limited by mass, shape, process, and other considerations. A special application of this principle is illustrated by the austenitic steels, wherein certain desirable physical properties can be obtained only by closely controlled finishing temperatures. Large forgings, and intricate shapes to be flowed into dies require relatively high finishing temperatures, and the required refinements of structure must be taken care of by subsequent heat treatment. With small and simple pieces, the finishing temperatures can be at or near the lower critical point, which produces refined structures that respond readily to simple heat treatment. A good example of the latter is the Damascus swords, which received repeated light workings at the critical and subcritical temperatures. The extremely refined structure thus produced responded to subsequent hardening, and a blade of remarkable properties was obtained.

Ingot Structure—The ingot of cast steel is made up of a mass of grains of varying sizes. The central portions of these grains are comparatively pure iron or ferrite, whereas the portions near the grain boundaries are correspondingly higher in the alloying elements and impurities. The resultant chemical heterogeneity is not entirely destroyed by diffusion or forging. Mechanical hot working causes

*Prepared by the Subcommittee on the Hot Mechanical Working of Steel. The membership of the subcommittee was as follows: S. C. Spalding, Chairman; J. P. Fleming, A. O. Schaefer, and W. R. Shimer.

these nonhomogeneous grains to be elongated in the direction of the working. Macroetching of a section parallel to the direction of working shows laminations or lines resulting from the chemical heterogeneity. Such lines are known as "flow lines" because they indicate the direction in which the metal "flowed" or was worked.

The physical properties of steel may differ markedly, especially in ductility and resistance to shock, in a direction parallel to these flow lines and perpendicular to them, particularly if the metal is not clean. Consideration must be given in forging practice to the service to which the forging is to be put. An example of this is the forging of rings. If rings are forged from a slab produced by elongating the ingot into a long block of rectangular section and subsequently trimming it to shape, certain sections of the rings will show radial flow lines and will probably have less ductility than the portions 90° away, which have tangential flow lines. For this reason, rings and forgings subject in service to tangential stresses are best upset or expanded in such a direction as to increase the physical properties in the desired way.

Mechanism of Hot Mechanical Working—The actual mechanism of the hot mechanical working of steel is divided into two classifications: Rolling and forging. The subdivision is by method of application of mechanical force. Rolling, as the term implies, works the metal by rolls; forging works metal by means of hammers, presses, and forging machines.

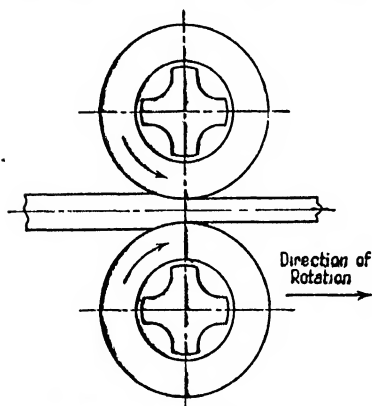


Fig. 1—Action of rolling.

Hot Rolling—Hot rolling is a mechanical method of hot working metal by causing the metal while hot to be fed between two rolls rotating in opposite directions. Hot rolling accomplishes three main purposes: First, reduction of cross sectional area; second, refinement of structure; and third, shaping of the metal into desired forms such as bars, sheets, rails, angles, and I-beams. The flow of metal in the rolling operation is continuous and almost entirely in a longitudinal direction (Fig. 1).

Blooming Mill—The rolling mill in which the first hot mechanical working of the cast ingot is done is known as the "bloomer" or "blooming mill." The function of the bloomer is to take the hot ingot as received from the soaking pit and break it down or reduce it to smaller size called a bloom or billet. This bloom is a semifinished product to be subsequently rolled on a billet mill or finishing mill, or used for forgings. The sizes of the majority of blooming mills range from 28-54 inches. The size is based on the distance from center to center of the pinions. Most bloomers are of the two high reversing type, which consists of two rolls mounted one above the other and reversible in the direction of rotation to allow for the passage of the metal back and forth through the rolls. Grooves or passes are cut in the rolls of a size and shape to accommodate the ingot and the various reductions desired. The usual procedure is a flat center pass called a "bull-head," used for breaking down the ingot to the size of the first pass, which is usually 13-14 in. wide. In addition, the blooming rolls contain several small passes, usually 8, 6, or 4 in. wide, depending on the finished bloom sizes required.

Operations on Blooming Mill—For an example, in rolling a 24 in. corrugated ingot to a 4x4 in. bloom on a reversing bloomer, the following method (which is for alloy steels and requires about 27 passes) is used:

The ingot is broken down under the bullhead (to 18x13 in.) by giving light drafts and turning each pass for the first four passes; it is then given 2 passes each way while being slabbled to 18x13 in. It is then turned and entered into the 14 in. pass, given 2 passes and turned; then 2 passes to 14x8 in.; turned and entered the 8 in. pass, given 1 pass and turned; then 1 pass to 5x8 in.; turned and entered into the 6 in. pass to 6x6 in.; turned and given 1 pass to 6x4 in.; then turned and entered into the 4 in. pass, and finished to a 4x4 in. bloom.

Billet Mill—In order to produce the size of billet necessary for use in the smaller finishing mills, it is customary to reroll the blooms, either with or without reheating.

ing, in some type of billet mill. The billet mill may be of the 3 high type, or may be continuous.

Finishing Mill—The billets or blooms, if not used for forging purposes, are rolled on smaller mills into bars of varying shapes and sizes. They may be rounds, hexagons, flats, or special shapes. Round bars generally are rolled in open pass rolls. Fig. 2 shows the passes and reduction of a 4x4 in. billet to a $\frac{3}{4}$ in. round. For special steels, more passes may be required, and the shape of the passes may not be the same as shown.

Flat bars are sometimes rolled in open pass rolls and many times are rolled in tongue and groove rolls.

Sheets—The practice covering the rolling of sheet and strip is given on page 818.

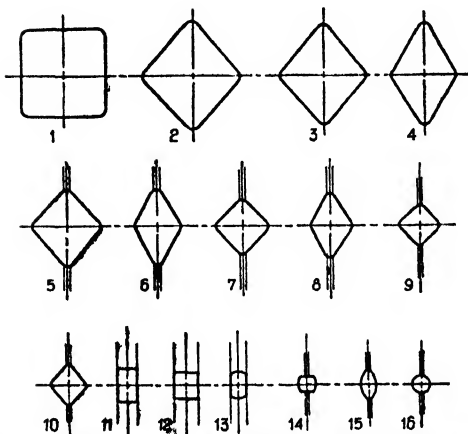


Fig. 2—Passes and reductions of a 4x4 in. billet to a $\frac{3}{4}$ in. round bar.

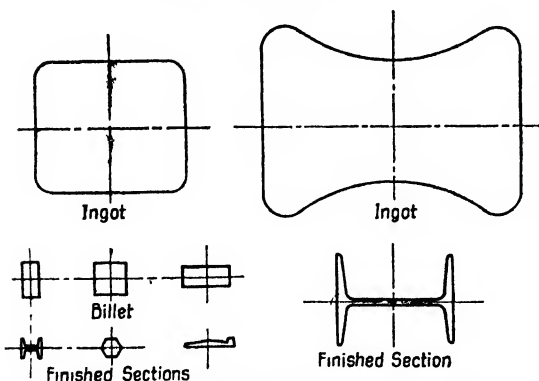


Fig. 3—Shapes rolled from ingots.

Shape Rolling—Steel is rolled into many varying shapes and special passes are made in rolls, depending upon the shape of the finished product. In the majority of cases, these shapes are rolled from a square or rectangular bloom or billet, all the shaping being done in the intermediate passes of the mill. In some cases, however, the shape of the finished product controls the preceding operations as far back as the ingot (Fig. 3).

Forging—Forging is used as a general term to describe the method of hot mechanical working of steel by the use of hammers, presses, and forging machines. A distinguishing point in the working of steel by forging is that the working for reduction or shaping takes the form of a locally applied force which displaces the metal under compression, after which

it is relieved and a new portion subjected to the working force. In rolling steel, the force is exerted by passing the material between constantly rotating rolls, and hence is continuously progressive in nature. A simple conception of the two processes is that forging exerts more of a kneading or hammering action, while rolling is more of the nature of a drawing operation (Figs. 1 and 4). For specific forging practices, see articles in this Handbook on forging.

Hammering—All steam hammers made today, except drop hammers, are double acting; that is, the falling weight or die is driven down onto the work by

steam. This increases the velocity of the head and increases the power of the blow.

The steam hammer consists primarily of a rigid frame supporting at the top a vertical steam cylinder. The piston is on the upper end of a rod which has the hammer head, termed "ram," and upper die at the lower end. The valve controlling the admission and exhaust of the steam is controlled by a lever usually attached to the lower part of the frame. The lower die and anvil is on a separate foundation from the remainder of the hammer in order to take the shock.

Various other types of power hammers find special uses today. Some are actuated by compressed air, others by motors.

Action of Hammering—The action of the hammer on the mass of hot metal is different from that of either the rolling mill or the press, because it strikes a more

or less sudden blow. The pressure is applied to the metal for a moment only, and before the metal has fully yielded, it is relieved. The metal, being elastic, recovers somewhat. For this reason, penetration of the effect of hammering tends to be limited. The surface of the metal is worked perfectly, whereas the center, if the piece is large, may hardly be affected.

Pressing—As the need for larger forgings grew, correspondingly larger ingots were cast. It was found that larger ingots had looser textures at the centers, and that it was difficult to thoroughly work these central portions under the hammer.

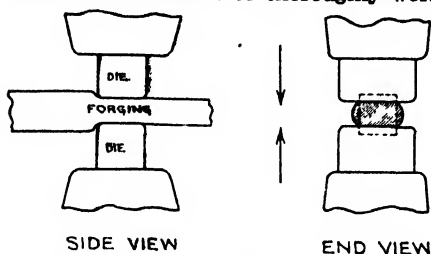


Fig. 4—Action of forging.

Forging presses consist essentially of a cylinder into which water at high pressure is admitted. The cylinder is located at the top of the press. The admission of water into the cylinder pushes down a ram to which is attached the cross head, on the lower side of which the upper die is fastened. The cylinder is held by vertical columns, which usually act as guides for the cross head. The lower die is supported on a base plate held by these columns at the lower ends. Thus the whole unit is self contained. Auxiliary lifting

cylinders, supplied with either steam or water are usually attached to the main cylinder or its entablature.

Tools for Hammers and Presses—Tools similar to those used by the blacksmith are applied to the steam hammer, such as tongs of different sizes with jaws of shapes suitable to handle the work. Swages are a form of semicircular die for finishing round bars. Heading tools and bolster blocks are used to forge upset ends on shafts. Forgings too heavy to be held on the dies by man power are carried by large tongs supported by a chain. Larger forgings are fastened onto a porter bar by means of a chuck on the end of the latter.

Rectangular sectioned blocks, held under the hammer on long rods, are called "pegs," and are used as gages or spacing blocks in bringing forgings down to size. Slicing bars are used to cut off and turn forgings.

Working under the press is simplified by the absence of shock in the process. Forgings can be held on the dies by direct suspension from cranes. Chain slings are used for the largest types, and the chain runs over a power sprocket on the upper end so that the forging may be turned; in some instances turning is done by ratchet levers. Many varying types of manipulators are used, suspended from overhead cranes, or running on tracks on the floor, which are designed to hold one end of the forging in a grip and move or turn it to any desired position.

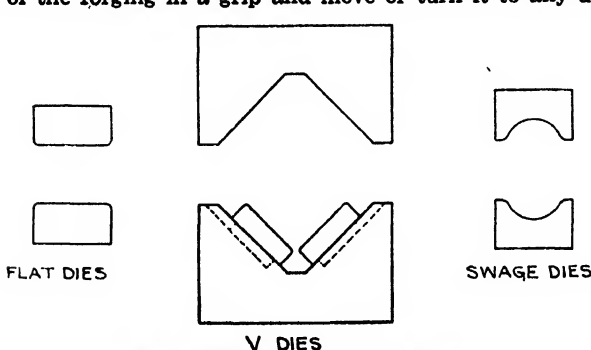


Fig. 5—Simple forms of forging dies.

Hammer Dies—The sizes and shapes of dies used under the steam hammer are many and varied and depend on the tools, the forgings to be made, and the forging practice followed. For the manufacture of bars or forgings similar to shafts, flat dies are usually used with the hammer, and the reduction from the ingot generally takes the bar to the form of a hexagon or octagon. It can subsequently be rounded up by knocking off the

corners of the polygonal section, or better, it can be finished with a top plain die and a bottom V. For the smoothest finish the bar may be trued up between swage dies each of which is practically semicircular. If this type of die is used, not much further reduction is often needed. Many round shafts are finished between flat dies on the hammer, ending up with a series of very light or "saddening" blows. Swage dies are generally used for tool steel bars. Simple forms of forging dies are shown in Fig. 5.

Press Dies—The dies used on a press are similar to those used on the hammer except that V-shaped bottom die is more general. The greater the power that can be exerted by the press, the larger the die surface that can be used, and therefore the more effective the press can be in working the central portions of the mass to be forged. It is also possible on the press to use a very narrow top die for expanding or drawing out the metal in any one direction.

Hammer and Press Operations—Except as covered in the next section, the principal forging operations performed either by the hammer or press are as follows:

1. Rounding up, cogging, or roughing. These first operations on the ingot aim to refine and rearrange the surface crystals and to consolidate the central portion of the ingot.

2. **Cutting or slicing.** This operation cuts blocks, billets, or forgings to length.

3. **Forging down or drawing.** This operation increases the length and decreases the diameter of the billet.

4. **Upsetting the forging** in a direction perpendicular to the longitudinal or major axis.

5. **Setting down.** This reduces the cross-sectional area of a portion of the forging, as the journals of a shaft are forged down. Large "set-downs" are accomplished under the press, using a V-tool to start the reduction. Large fillets should always be allowed.

Hollow Forgings and Piercing—Many machine parts require forged cylinders or similar sections. Large rings, cylinders, or hollow shafts can be advantageously worked in this way. For this purpose the ingot or block is pierced, punched, trephined or bored. As the name implies, piercing consists of boring into the mass with a pointed punch. The punch has to be of a material hard enough to penetrate, resist abrasion, and not be too severely affected by the temperature. Cylinders with one solid end may be pierced while held in a cylindrical die. In cases of this sort, the pointed punch would be followed by successively larger, slightly tapered, and blunt nose punches to increase the bore and forge out the walls of the cylinder against the die.

Punched Forgings—Blocks intended for ring or similar forgings are often punched under the hammer or press. The punch may be in the form of a tapered cylinder with a slightly rounded flat nose. It is usually pushed part way through on one side, the forging turned over, and the hole punched through from the other side with a slightly larger punch.

Forged Expanded Rings—Rings may be expanded under the hammer, using a horn attached to the bottom die. Large rings are expanded under the press on a mandrel, supported on standards close to the ends of the forging. Large cylinders are drawn out on mandrels under the press, the mandrel being supported for expanding, and unsupported for forming to shape, using a top plain die and a bottom V die.

Hot Die Forging (Drop Forging)

By R. W. Thompson*

Die forging conducted under a hammer is most commonly referred to as "drop forging." It is the operation of forming a metallic shape by repeated blows on a bar or billet between a pair of dies which have the desired impression of the finished forging shape.

The drop forging hammer contains a ram which carries a die operating in a vertical plane and an anvil block in which is keyed a stationary die. The two dies are matched together so that the impressions in each are in perfect alignment permitting the impact to cause the metal to fill the cavities for the production of the prescribed forging design. The means by which the ram is lifted determines the name by which the hammer is known.

Steam Drop Hammers—The ram and movable die are actuated by a steam valve which regulates the height of drop and force of the blow through the action of a piston rod operating in a steam cylinder. These hammers are known as double acting hammers, because the steam is utilized for lifting the die upward, as well as for forcing it downward. Steam hammers range in capacity from 500-50,000 lb. and are so rated on the basis of the combined falling weight of the ram and piston rod. Because of their great force of impact and rapid operation, steam hammers are generally used for drop forging the heavier forging parts and also those designs which require numerous hammer blows to complete the various die operations in their manufacture.

Air Drop Hammers—Hammer construction is the same as for steam drop hammers with the exception of the valve mechanism. Power is derived from compressed air instead of steam and with operation equally satisfactory. The selection of air for power is a matter to be judged by the economical advantages offered in the particular plant or location.

Board Drop Hammers—In a board drop hammer the ram is lifted by means of one or more boards keyed to the ram which pass between two rollers at the top of the hammer. The boards are rolled upward and then mechanically released, permitting the ram to drop when the desired height is reached. The power for this operation is either by direct motor drive or by line shaft and pulleys.

In the board drop hammer the force of the impact is dependent upon the gravity attraction of the ram and for this reason it is sometimes known as a gravity hammer. These hammers built to standard specifications have a falling weight or capacity of 400-10,000 lb., and naturally are used in the production of the smaller and lighter forging parts.

Helve Hammers—Some die forging is conducted with hammers in which the force is not dependent upon the vertical fall of the ram. This type of die forging work is not ordinarily considered as drop forging. These hammers operate by an oscillating wooden beam pivoted at one end and carrying at the free end the ram head and movable die. The beam is lifted by a rotating shaft carrying a series of cams which raise the hammer and allow it to drop suddenly in a succession of blows with lightning-like rapidity.

Forging hammers of this type do not deliver a very forceful blow and therefore depend upon their fast and continuous operation for forging production. Only small forging designs are made with these hammers, being used more often as an auxiliary unit in conjunction with a drop hammer wherein they serve to draw or reduce certain sections of a forging part.

Dies and Tools—A blueprint or sketch of the forging showing the necessary draft angles, radii, fillets, and amount of finish required, is submitted to the die shop for their guidance in making the dies for the forging. It is the purpose of the forging dies to produce as many forgings as possible, each to the tolerances prescribed and commercially duplicates of each other.

Forging dies are designed so as to give the required mechanical working to a bar or billet in order to produce the finished forging shape with a minimum of

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internal stress. Their construction is also designed so as to maintain the grain fibers inherent in the rolled bar in a continuous and unbroken manner in the forging and whenever possible at right angles to the direction of stress or shock in service.

Forging dies for small forgings are oftentimes designed with multiple impressions, producing several pieces in one flashing. The use of a larger hammer in producing the forgings in multiples is generally thought more economical, providing sufficient quantities are to be made to justify the extra die expense.

Die blocks in most general use are made of alloy steel and are heat treated to a hardness which is governed by the size of the block and the design of the forging for which they are to be used. It is common practice to use dies hardened before sinking when the hardness required is less than 60 scleroscope. For dies requiring a hardness of 60 scleroscope or over, the hardening of the blocks is conducted after the die sinking is completed.

The necessary impressions in a die for a certain forging may be described as fuller or swager, edger or roller, blocker, finisher, and cutoff. The fuller reduces the side of the section of the material. The edger conforms the material to the area of the respective sections of the piece to be forged. The blocker gives the forging its general shape, and the finisher completes the forging design. The cutoff is used to cut the forging from the bar so the operations may be repeated.

In addition to the impressions which are used for the various operations of drop forging production, the dies are also provided with a gutter, which is the portion of the die around the impression that has been relieved to provide space for the excess stock.

Standard draft angles in the dies of 7° are in general use, although quite often in cases where forgings are designed with deep holes it is desirable to use 10° draft for better forging results. The draft or taper on the side walls of the die impressions are necessary for the removal of the forging from the die, and should be taken into consideration at the time the forging is designed.

After a set of dies has been completed, the two halves are matched together and molten lead and antimony are poured into the finishing impression, producing a model of the forging which is known as a lead cast. The lead cast is used for checking purposes and is measured with a shrink rule which compensates for the shrinking of the material. The amount of shrinkage varies a little with the type of material and shape of the forging, but may be generally considered as $\frac{1}{8}$ in. to the foot.

The flash or excess metal forced out between the dies in filling the impression to its complete contour is trimmed from the forging in a mechanical press. Trimming dies are furnished for either hot or cold trimming, depending upon the method desired. Hot trimming is done on large forgings and certain alloy steels which would fracture if cold trimmed, and usually is conducted in a press adjacent to the hammer at the time of the forging operation. Small forgings are usually trimmed cold. They are likewise trimmed in a press and most generally in a separate department.

Trimming dies are made of tool steel and are shaped to fit the outline of the forging at the parting line of the dies. The trimming punch, also of tool steel, is shaped to the contour of the top of the forging to be trimmed. The trimming tools for cold trimming are always quenched and tempered to a hardness that will produce the best wearing and cutting edges for the particular forging design. Hot trimming tools, except trimming dies, are usually quenched and tempered, but are sometimes used in either the annealed or normalized condition. Trimming dies are either quenched and tempered or surfaced with a hard facing alloy.

General—Drop forging operations are conducted by working from the bar end, cut slug, and individual billet. In working from the bar, one or more forgings are made before the end of the bar is reheated. The number of forgings cut off at each heating is dependent upon the size and design of the forging.

Cut slugs of a weight necessary for the forging of one piece are forged by the hammer upset method. The slug is placed on end on the die and upset or pancaked to form the forging. This method has a particular advantage in the control of grain fibers and is used generally in the production of gear blanks, hubs, and flange forgings.

Forgings of medium and larger sizes are made from billets sheared or sawed to the individual length required for the production of one piece. Large and massive forgings oftentimes require two or more hammers to effect their com-

pletion; each hammer providing progressive steps by aid of proper dies and tooling for the necessary operations.

In forging the bar or billet into a completed drop forging design, the metal is further refined into a dense tough fiber structure throughout the entire cross section. This refinement of the forging bar improves the physical properties, increasing the impact, tensile, torsional and compressional strength.

For information on heating, see the article in this Handbook on "Heating Steel Bars for Forging."

Inspection—Forgings are checked periodically during hammer operations for mismatch, dimensions, and tolerances, as well as for detection of laps, cold shuts and seams.

After trimming, the scale or surface oxide is removed by any one of a number of methods. The principal ones are pickling, sand or shot blasting, and tumbling.

The final inspection, in addition to a recheck of conditions examined for during hot inspection, may be further classified as to mistrimmed, scale pits, not filled, underweight, overweight, and any physical or microscopic tests prescribed in the specifications.

Hot Upset Machine Forging

By W. W. Criley*

Definition—Hot heading, upset forging, or more broadly machine forging are terms applied to the hot deformation or plastic flow of steel in an upsetting forging machine commonly in use. It primarily consists of holding a bar of uniform cross section, usually round, between grooved dies and applying pressure with a heading tool on the end in the direction of the axis of the bar so as to upset or enlarge the end.

Description of Forging Machine—Present day forging machines, some of which weigh in excess of 200 tons, and are capable of 2000 tons pressure, are an outgrowth

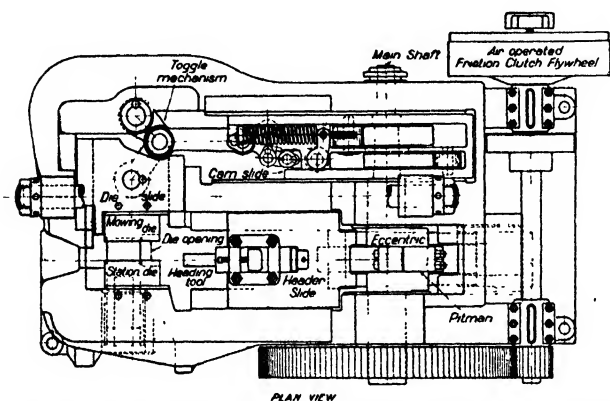


Fig. 1—A plan view of a forging machine showing arrangement of working parts.

of earlier small machines built mainly for hot heading bolts and for producing nuts by an added punching operation. Such machines were rated on the basis of the maximum size bolt they were capable of heading, and this method of rating has, after a fashion, been adhered to and extended to include even the largest machines, while the same fundamental forging processes are employed to produce a great variety of upset and pierced forgings, weighing from a few ounces up to several

hundred pounds. Any of the malleable materials can be forged by this method of compression deformation including wrought iron, alloy steel, copper, bronze, aluminum and others.

A plan view of a forging machine is given in Fig. 1. The machines in general use are mechanically operated from a main shaft which drives a main or header slide horizontally by means of an eccentric and pitman, and also drives a die slide or grip slide with horizontal movement at right angles to the header slide, usually through a toggle mechanism. Power is supplied to the machine flywheel by electric motor or line shaft, and, excepting on small continuous motion machines used for forging and shearing off bolts and rivets from long bars, a clutch provides for "stop motion" operation, placing the movement of the slide under the control of the operator.

The die elements in which forging takes place consist of two "dies" or "gripper dies," one stationary and one moved by the die slide, which have matching faces with horizontal grooves to grip and hold by friction the forging stock, and "headers" or "heading tools," carried by the header slide in the plane of the die work faces, and matching the die impressions. The travel of the moving die is designated as the "die opening" and its timed relation to the movement of the header slide is such that the dies close during the early part of the header slide stroke. That part of the forward header slide stroke which takes place after the dies are closed is termed the "stock gather" and the amount of header slide return travel before the moving die starts opening is called the "hold on" or simply "hold."

For forging, the operator places a bar of forging stock heated on the end in the first groove in the stationary die against a movable stock gage to secure the correct volume of stock in the forging impression. When he trips the clutch, the moving die closes, grips the stock and holds it while the heading tool advances and

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Prepared for the Subcommittee on Forging. The membership of the subcommittee was as follows: Adam Steever, chairman; R. W. Thompson, F. B. Foley, O. W. Ellis, H. M. Spears, W. E. Jominy, W. W. Criley, and J. H. Friedman.

upsets the end of the bar which projects beyond the gripping grooves and is termed "working stock." The operator then transfers the bar to other die grooves, striking it generally but once in each groove, the number of grooves depending upon the steps required to complete the forging.

Forging is not limited to simple gripping and heading operations, as the transverse action of the moving die and the longitudinal action of the heading tool is available for forging in both directions, either separately or simultaneously. The die motion, in addition to gripping, can be used for swaging, bending, shearing, slitting, punching and trimming; and the heading tools, in addition to upsetting, are used for punching, internal displacement, extrusion, slotting, trimming, bending and other operations.

As the cavities formed by the two dies and the heading tools open in two planes at right angles, and as the working stock can frequently be totally confined in these cavities during forging, and subjected to a hydrostatic-like pressure causing it to completely fill the impressions, a great variety of shapes can be forged and removed from the dies without difficulty as shown in Fig. 2.

Forging Machine Requirements—In order to produce forgings to the close Standard Tolerances drafted by the Drop Forging Association, February 11, 1937, accurately filled out and free from defects, the modern forging machine must have (1) a rigid frame with minimum transverse and longitudinal distortion under forging pressures; (2) a powerful die grip to hold the stock securely and prevent the dies from spreading open with resultant formation of flash; (3) accurate die slide and header slide alignment to prevent mismatch of the impressions of the two dies and heading tools, and to produce deep concentric holes; (4) ample heading power to forge to accurate thickness and drive the stock into remote parts of the die impressions to properly fill them; (5) a fast starting clutch and operating convenience so that the multiple operations required to produce difficult forgings can be performed before the working stock loses its forging temperature.

"Die opening" is the factor which determines the maximum diameter upsets which can be formed on a given machine, transferred between the dies, and withdrawn through the throat without pushing forward of the dies and lifting out over the top. The "stock gather" determines, not so much the amount of stock that can be upset, as the diameter of stock itself, but has important bearing on the depth to which internal displacement can be carried in a single operation. The die height determines the number of progressive operations which can be accommodated in one set of dies.

Die Construction and Design—Proper dies are also essential to the production of sound forgings. So that impressions will retain their correct shapes, particularly at the part line, the dies must be constructed of suitable grades of die steel for hot work with resistance to heat, pressure, and abrasion, and selected with reference to the specific properties required, the speed of forging, and the quantity of forgings to be produced. See *Steels for Forging Dies*, page 1018. The absence of impact in this method of forging makes it possible to build up dies with inserts, thereby, without prohibitive cost, utilizing a variety of high grade steels to exactly meet the needs at different locations in the impressions. This gives increased durability and makes the more vulnerable points inexpensively renewable. Fig. 3 illustrates inserted dies and tools for upsetting gear blanks.

Factors Governing Upsetting—The number of operations employed to produce a forging are determined by the length and diameter of working stock, the shape

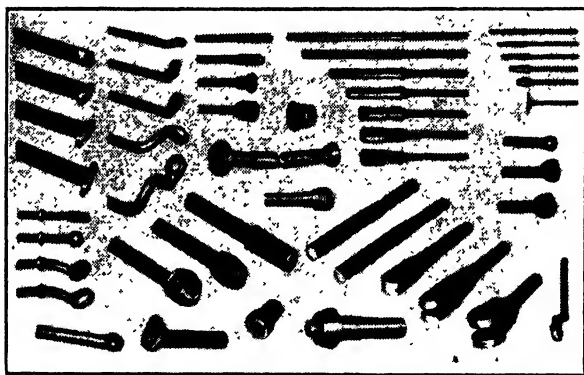


Fig. 2—A group of upset forgings, some of which show the successive forging operations.

of the forging itself, and any special internal fiber arrangement necessary to produce the desired physical properties in the finished forging. Successive upsetting operations should each fill the die cavity completely, consequently be of the same volume and sound, as subsequent operations rather than ironing out defects, tend to imbed them. The most common defects to be avoided are cold shuts, that is, closed folds in the surface metal, re-entering fiber or internal folds, and included flash.

The generally recognized rules governing the upsetting or gathering of stock without injurious bending and resulting cold shuts are:

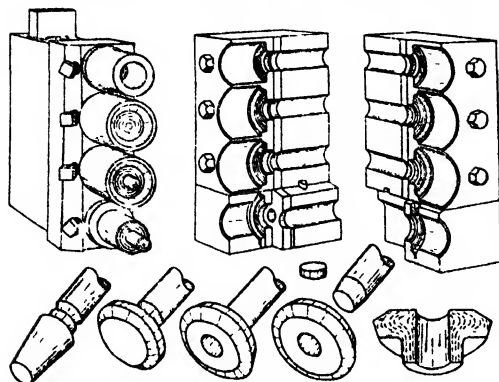


Fig. 3—Inserted dies and tools for upsetting gear blank with a final combined shearing and punching operation with progressive forging steps and section showing looping fiber arrangement of completed forging.

I. Working stock up to a maximum length of three diameters can be upset without support to prevent bending. Working recommendation $L = 2\frac{1}{2}d$.

II. Working stock longer than three diameters, in order to prevent injurious bending, must be supported by either die or heading tool impressions of a maximum diameter of one and a half times the diameter of the working stock. Working recommendation $D = 1\frac{1}{2}d$.

Die Impressions should be as nearly the full length of the working stock as will permit gaging, and the recess in heading tool should be at least two-thirds the length of the working stock and belled at the opening to prevent a sharp shoulder. Supporting impression should not be partly in the die and partly in the tool.

Repeated applications of the second rule make possible the upsetting of great lengths of original bar stock, and with the progressive increase in the diameter of the "working stock," the amount of "stock gather" can be increased on succeeding operations. Preference is given to recessed heading tools for stock gathering, owing to their greater durability and freedom from the flash, which tends to form at the die part-line when upsetting in grooves in the die and around the periphery of the plunger-like heading tool.

Square stock is governed by the same rules as round, using "d" as the mean of the flat and diagonal dimensions, but rectangular stock bends so easily flatwise that the short rectangular dimension is the one that must be used in the above formulae.

Fiber Arrangement—In gear forgings particularly, and other highly stressed parts, effort is made to secure maximum strength through advantageous internal fiber arrangement, as illustrated in Fig. 3. This can be controlled by the shape of the preliminary upsets, and re-entering or sharply folded fiber can be avoided. Progressive operations should be shaped so as to be easily filled by hydrostatic pressure within the hot metal.

Flash—Flash can be avoided best by locating the part line between the heading tool and the die at the point of the impression which fills last, and, if flash is unavoidable, it should be located where it can be easily removed by trimming, chipping or grinding.

Pierced Forgings—Internal-recessed, or deep-pierced forgings are produced most easily by the progressive piercing method as contrasted with extrusion. In this method, as illustrated in Fig. 4, the metal from the interior of the full length blank

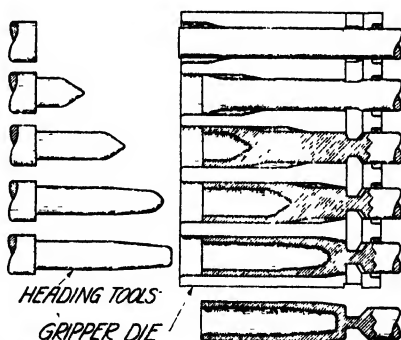


Fig. 4—Progressive steps in deep piercing a shell by internal displacement method, showing cross section of progressive operations in die impressions prior to being acted upon by piercer.

is progressively displaced to the outside of the die cavity without excessive pressures or abrasive flow to cause rapid deterioration of the die elements.

Tubular Upset—With the extensive use in the oil industry of seamless steel tubing with threaded joints of full body strength, and the use of both seamless and welded tubular structural members, where minimum dead weight and maximum strength are required, the upsetting of tubing has assumed importance. Light wall thickness being easily collapsible, offers difficulty in gripping between the dies to prevent slippage, frequently necessitating the use of a backstop; rapid cooling makes reheats necessary; and the wall thickness limits the extent to which upsetting can be carried in a single operation without injurious folds. Since buckling occurs to the outside, an increase in wall thickness of only about forty per cent can be accomplished by a single outside upset; whereas, with the outside closely supported by the dies, the wall thickness can be practically doubled by a single inside upset. This makes it advantageous, where permissible, to gather the stock with internal upsets, then force this stock into an external impression by means of a tapered nose on the heading tool.

Since each upset forging offers its own particular problem, each must be handled on an individual basis in a manner adhering to the broad fundamentals of sound upset forging practice.

The Piercing of Steel

By Stevenson Findlater*

The forging operation in the production of seamless steel tubes is classified under four general headings: rotary piercing, hydraulic piercing, cupping, and extrusion. Of these four methods, rotary piercing is employed almost universally for quantity production.

Rotary Piercing—In the rotary piercing of steel (Fig. 1), the principle of helical rolling is employed. The two steel rolls which bring into play the forces used to produce the cavity in the work piece are positioned side by side and have their axes inclined at opposite angles (6-12°) with the horizontal centerline of the mill. The shafts of these rolls are mounted in bearings, which can be adjusted laterally in

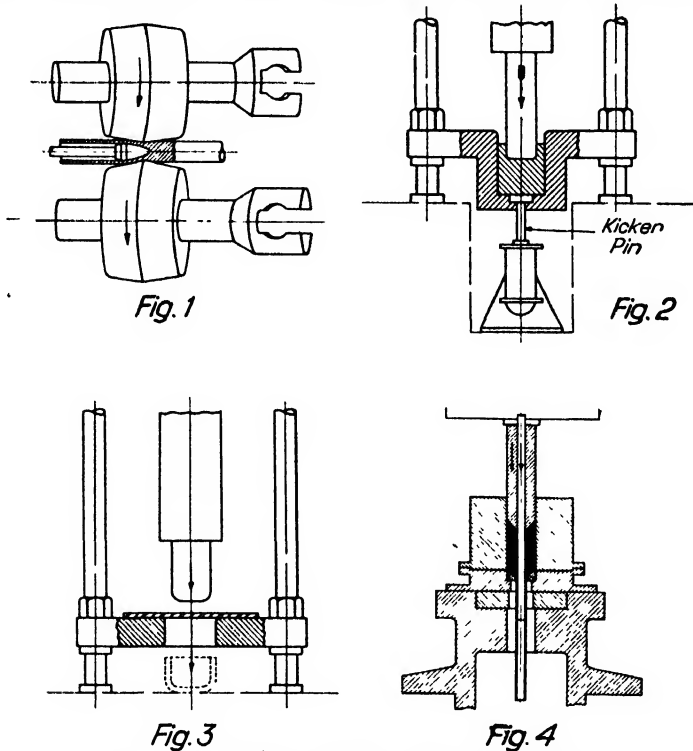


Fig. 1—Mannesmann pierces, piercing solid billet.

Fig. 2—Hydraulic piercing, solid blank.

Fig. 3—Cupping operation, plate.

Fig. 4—Extruding solid billet.

the housing to permit the space between the rolls to be properly set for the size of work piece being rolled. The roll surfaces are contoured so that in a horizontal plane through the centerline of the pass, the space between the rolls converges toward the delivery side for a length of about ten in. to a minimum, called the "gorge," and then diverges for approximately twelve in. to form the pass outlet. The elevation of the centerline of the pass is determined by two guides, one of which is mounted above and the other below the center of the mill.

Between these guides in the pass outlet a tapered piercing mandrel is held in position on the end of a water cooled mandrel support bar located on the delivery side of the mill. The opposite end of this bar is mounted in a thrust bearing which is carried in a reciprocating carriage that is latched stationary during the piercing

*National Tube Co., Pittsburgh.

operation. The pointed end of the piercing mandrel extends just beyond the gorge toward the entering side of the rolls.

A solid round bar or billet of the proper length and diameter (2-14 in. dia. by various lengths to 18 ft.) to make the size and weight of tube desired, is heated uniformly to the usual temperature for rolling light sections. With the rolls revolving at a constant speed (800-1000 surface ft. per min.) the heated billet is transferred to a horizontal trough which positions the axis of the billet coincident with the centerline of the pass.

The heated billet is pushed forward into the space between the rolls, which has been adjusted so that the gorge is approximately $\frac{1}{4}$ in. less than the dia. of the billet. As soon as the billet has contacted the rolls, the force of the pusher is removed. Owing to the obliquity of the roll axes, the motion imparted to the billet by the rolls is one of rotation and axial advance. When the leading end of the billet has advanced to the gorge, it encounters the nose of the piercing mandrel. The grip of the rolls is sufficient to continue the advance of the work piece against the retarding effect imposed by the piercing mandrel. Once the end of the piercing mandrel has penetrated the axial center of the billet, the mandrel serves as a third roll so that, with a properly designed pass, the metal of the work piece is helically rolled over the piercing mandrel (rather than extruded) to produce the hollow shell. These shells are produced in lengths up to 40 ft., in from 10-30 sec. It is to be especially noted that the amount of metal displaced increases considerably as the size is increased. Difficulty with this condition has been overcome by further reducing the wall thickness of the hollow shell through additional rolling in a second piercing mill. This practice has permitted the total displacement to be divided between two operations when large tubes are made. Additional rolling operations are performed on the pierced shells to produce finished tubes.

Hydraulic Piercing—In hydraulic piercing, a heated solid blank, usually of square section, is dropped into a cylindrical container located directly in line with the plunger of a hydraulic ram. The descending plunger causes the piece to assume the shape of the cylindrical container as it is displaced up and around in the space between the plunger and container. When the down stroke has been completed, the plunger is withdrawn by reversing the direction of the ram, after which the pierced blank or cup is ejected by a kicker pin. When this process is augmented by hot drawing, whereby a powerful plunger forces the cup through a push bench in which a series of annular dies or grooved rolls are installed, the length of the piece may thereby be extended to form a tube.

Hydraulic Piercing (Fig. 2) is used in the production of large and small cylinders, such as water bottles, gas, and air bottles, and as the primary operation in manufacturing tubes by the "push bench" method.

Cupping—In the cupping process (Fig. 3), steel plate of required thickness is sheared, machined or gas cut to circular shape. The heated plate is accurately positioned over a die which is centrally located beneath the plunger of a hydraulic ram. The descending plunger forces the plate through the die to form a cup which is removed when the plunger has been withdrawn. To avoid buckling when cupping, the annular opening between the plunger and the die is proportioned to exceed the initial thickness of the plate. Requisite alterations in the length, wall thickness, and diameter of the heated cup are subsequently made in a push bench. This process is in common usage in manufacturing containers for oxygen and acetylene and for other cylinders which require a closed end.

Extrusion—The extrusion process (Fig. 4) has not been used for the production of steel tubes in the United States, although several European plants employ it. The elevated temperatures essential to effect the necessary plasticity of a steel work piece requires that the operation be rapid to avoid temperature drop and severe tool wear during the working stroke of the press. This requisite has resulted in the development of the practice known as "impact extrusion" in which the work stroke in extruding tubes 30 ft. long is completed in less than three seconds. In this process, either bored or solid rounds are heated and dropped into a cylindrical container, in the bottom of which a die is mounted directly below a crank or hydraulically operated plunger. When solid rounds are used, a differentially actuated piercing punch is enclosed within the extrusion plunger. In operation, the weight of the extrusion plunger is allowed to rest on the upper surface of the work piece, while the piercing punch is forced through the work piece and die. When the end of the piercing punch has passed through the die, the piercing and extrusion plungers are locked together, permitting the piercing punch to act

as a moving mandrel, while the rapidly descending extrusion plunger forces the work metal through the annular opening between the die and piercing punch. Pressures in excess of 90,000 psi. are produced within the container in producing the 20:1 section reduction usually employed. When the plungers have been withdrawn, a flash which remains in the bottom of the container is sheared off, thereby releasing the extruded tube from the die.

When bored rounds are used, the piercing punch is usually attached directly to the lower end of the extrusion plunger. The operation is the same as when solid rounds are used, except that piercing is omitted.

Because of the terrific pressure required, the application of the extrusion process to the manufacture of steel tubes has been limited to tubes less than 5 in. in dia.

Steels for Piercing—The piercing processes described above have enabled seamless tubes to be made from most types of steels and many nonferrous alloys. Usually, killed open hearth and electric furnace steels are preferred, but satisfactory seamless tubes have been made from capped open hearth steels when melted under certain prescribed conditions.

Most commercial steels are available as seamless tubes. The S.A.E. steels, high sulphur free machining steels, ball and roller bearing race steels, and many stainless and heat resistant alloys are now satisfactorily pierced. In general, steel alloys which are two phase, austenitic and ferritic, at forging temperatures (2000-2300°F.) are difficult to pierce by the rotary process but can be formed in the cupping or extrusion processes. Nonferrous alloys which contain more than one phase are also more readily pierced by extrusion methods. Extrusion is little used on steel because the high forging temperatures and high pressures are severe on extrusion tools, but the process has been highly successful on nonferrous alloys.

The steels used for seamless tubes must have good characteristics, both with respect to surface and internal soundness, on account of the severe forging operations involved in piercing. Sound dense steel, as shown by deep etching tests on cross sections, free from porosity and ingot pattern, is most satisfactory for seamless tubes. Tube steels must also be free from surface defects, so it is common practice before piercing to peel rounds or plane square sections in addition to treating them by conventional chipping methods.

Extrusion of Metals

By D. K. Crampton*

Introduction—The term "extrusion" as applied to metals comprises essentially the application to a relatively massive billet or blank sufficient pressure to cause the metal to flow through a restricted orifice, thereby forming a greatly elongated section of uniform but relatively less massive volume. The extrusion may be either hot or cold. As the terms indicate, hot extrusion is above the recrystallization point of the metal which continuously recrystallizes and is not work hardened during the process. In cold extrusion the metal never reaches the temperature of incipient recrystallization. It may, therefore, be considerably work hardened by the process.

Both mechanical and hydraulic extrusion presses are used but the tendency today is almost exclusively toward the hydraulic type. These are more flexible, compact, easier to control, and less subject to damage from improper operation. The presses most used at present vary in capacity from 200-4000 tons.

Hot Extrusion of Lead and Lead-Base Alloys—The ordinary extrusion of low melting point metals such as lead, tin, zinc, lead-tin alloys, pewter or britannia metal is usually carried out either at room temperature or at least fairly low temperatures.

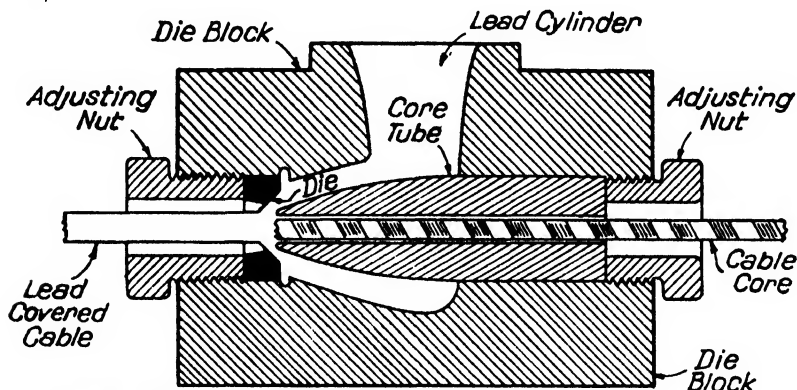


Fig. 1—Section through die block assembly used in making lead cable.

The pressures required to extrude will vary considerably with the alloy as well as with the temperature, size of section, and number of sections per die. Soft lead usually will require unit pressures from about 40,000 to about 60,000 psi. For any given section the copper-bearing leads will require roughly 10-20% more pressure, and the antimonial and tin-bearing alloys possibly 50% more.

The speeds permissible also vary greatly. With soft and copper-bearing leads and large sections, this is limited only by the capacity of the pumps. In small sections it may in some instances run as high as 200 ft. per min. However, with the other alloys mentioned, speeds of from 20 to not over 80 ft. per min. are necessary to prevent checking. The physical properties vary somewhat with the speed, better values resulting from the lower speeds.

Cable Sheath—The equipment for extruding cable sheath includes a melting kettle with connection to the extrusion press. The usual press is hydraulic and so arranged as to take intermittent charges of molten lead from the kettle. This press is vertical, and the cylinder in a commercial machine might hold approximately 1800 lb. of lead. At the lower end of the cylinder, there is a die block forming an annular path for the flow of lead around a core through which is fed the cable to be sheathed. A section through a die block assembly is shown in Fig. 1. The molten lead is charged into the press at about 750°F. and it normally requires approximately 7-8 min. for solidification and reduction to a suitable temperature for extrusion (about 425°F.) at which time the pressure is applied. The now solid lead is forced through an annular orifice between the core block and the die and

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on to the cable, the product normally being coiled on a large drum as it comes from the press. The presses commonly used for this work have a capacity of from about 600-2500 tons and can produce up to 5500 lb. per hr. or slightly better.

One of the difficulties encountered in the finished cable sheathing is a seam due to entrapping oxides or other foreign materials between successive charges of lead. There is, of course, at all times a layer of dross on the surface of the molten lead and even with the utmost care, some of this may be entrained, tending to prevent perfect coalescence of the divided lead stream as it flows around the core block or at the interface between two successive charges of lead fed into the cylinder. When an appreciable quantity of such dross is occluded a seam or a weak spot results, which is likely to fail in service.

Hose Encasing—In the manufacture of rubber garden hose and of rubber covered wire it is common practice to vulcanize the rubber while it is encased in a sheath or mold of lead. This lead mold is extruded over the hose in quite similar manner to that used in the production of cable sheath. In the present instance, precast lead billets are fed into the press instead of molten lead. This is possible because no particular precaution against forming of seams or the inclusion of dross need be taken. By eliminating the necessity of waiting for the molten metal to freeze, approximately double the production is obtained.

While cold billets may be fed, they are preferably heated to about 260°F. The container itself ordinarily is heated to a temperature of approximately 350°F., and the actual temperature of the lead, as extruded, approximates the latter figure. Pure soft lead is ordinarily used, and this is extruded as fast as the equipment permits, speeds up to 100 ft. per min. being attained. After the lead encased hose is taken from the press, it is vulcanized by hot water under pressure which varies from 150-250 lb. pressure. The lead is subsequently stripped from the hose and is remelted for further use in the same operation. Under ordinary conditions billets weighing approximately eleven to twelve hundred lb. are used, and the lengths obtained depend upon the size of the hose encased. The lengths run from 250-1000 ft. in normal production.

Lead Pipe—Vertical presses are used for extrusion of lead pipe. Usually, but not always, the lead is poured in and solidified before extrusion. The die is held in the hollow ram and the extruded pipe comes out at the top of the press and is coiled as produced. The presses commercially used normally run from about 400-1000 tons capacity and the individual charges vary from 200-500 lb. depending upon the size of the pipe made. Soft lead can be extruded quite fast, the speed being determined largely by the capacity of the pumps. Speeds of 50-60 ft. per min. are not uncommon in practice.

Hot Extrusion of Tin-Base Alloys—Various solder alloys are extruded in the form of wire. These are mostly tin-lead alloys containing from about 40-80% tin. Many other tin-base alloys are produced in lesser amounts. A large part of this production is in the form of solid wire, but a considerable amount also is resin or other flux-cored solder. In the case of the solid wire, solid billets are extruded in an ordinary rod extrusion press, but in the case of flux-cored solders, resort is made to a procedure roughly similar to that employed for hose encasing or cable sheathing. The presses used for solders may be either vertical or horizontal but are small, ranging from about 200-500 tons and using billets about 2½-4 in. in dia. and 8-16 in. long. Resin core solders are extruded in a single strand, but solid wires in multiple strands, sometimes as many as 12 per die.

Most solder alloys must be extruded at fairly low speeds to prevent checking of the surface, about 30 ft. per min. being usual. The pressures and temperatures run about the same as in the cable sheath extrusion.

A considerable quantity of various ornamental shapes are extruded from pewter, or as it is sometimes called, britannia or white metal. The alloy is of variable composition, of tin-base, and normally contains anywhere from 5-15% antimony, from 0-3% copper and 0-15% lead. These extruded shapes are used for moldings on various pewter pieces such as vases and pitchers. They are attached to the plates by the use of low melting point solders.

An ordinary horizontal rod press of about 250 tons capacity is used, the billets being about 2½ in. in dia. by 8 in. long. The alloy is extruded at a temperature of 140-150°F., but very low speed must be used to prevent checking of the edges. In some cases this might be as low as 10-20 ft. per min. The pressures used will vary from 40,000-100,000 psi.

Hot Extrusion of Copper and Copper Alloys—The equipment used for extruding copper-base alloys is different in many respects from that employed for the low melting point alloys although the principles involved are much the same. Both mechanical and hydraulic presses have been used but the mechanical ones are much in the minority and the present tendency is entirely toward the hydraulic.

Rods are always extruded from horizontal hydraulic presses, but for tubes both horizontal and vertical ones are used. For tube extrusion the smaller presses of capacities up to perhaps 1100 tons are prevaillingly vertical and the larger ones invariably horizontal. Tube presses up to 4500 tons are in use and rod presses up to about 3500 tons.

The extruded nickel silvers are used mainly for their white color, high strength and fair machinability. While they can be extruded quite readily, the permissible temperature range is narrow compared to the other extruded alloys and it is relatively difficult to extrude them in small sizes or very complicated sections.

The linear speed of extrusion in rod presses varies enormously with the composition of the alloys, the size and shape of the section, the temperature and the presence or absence of an accumulator. In rod presses, speeds from approximately 20 to well over 500 ft. per min. are commercial. In tube extrusion presses using an accumulator, the linear speed is in some instances as high as approximately 1000 ft. per min.

The pressure required to extrude also varies quite widely depending on much the same factors as those which control speed. With the softer alloys, larger sizes, and simpler shapes, pressures as low as approximately 30,000 psi. are used. With harder alloys, more complex shapes and relatively smaller sections, pressures up to 120,000 psi. are found necessary. In general, when the press is operated direct from the pumps, the pressure required to start flow through the die is fairly high. Immediately after starting, the pressure falls to a fairly low figure which holds relatively constant until near the end of the extrusion when the pressure may rise to at least double that required for starting. This effect, as well as the marked effect of temperature, are both shown in Fig. 2.

Rods are usually extruded straight, on to either a stationary or traveling cooling bed, and are subsequently drawn to finish. Any material which is ultimately to be drawn into rather small diameter rods or wire is normally extruded in sizes from about $\frac{3}{8}$ - $\frac{1}{2}$ in., depending on the alloy, and coiled hot as it comes from the die. In these smaller sizes, several rods may be extruded from a die, sometimes as many as four. Two-hole dies are commonly used up to about 1 in. but larger rods are invariably extruded through a single hole die. "Pipe" is a defect more or less inherent in the extrusion of brass rods and is caused primarily by the flow of the oxidized surface of the billet to the center during the extrusion process. In the higher copper content alloys having a single alpha solid solution structure little or no central pipe is incurred, because the oxidized material comes to the surface of the extruded rod, frequently giving the appearance of a shag bark hickory tree. In such instances the defective surface has to be removed by scalping before the rods can be drawn to final size. In Table I and II are given the copper-base extruding alloys and their physical characteristics.

Hot Extrusion of Aluminum-Base Alloys—The equipment used for extruding aluminum alloys is similar to that employed for the copper alloys. The presses are usually horizontal ones with capacities ranging from about 500-4,000 tons.

Although practically all aluminum alloys can be extruded if necessary, only a

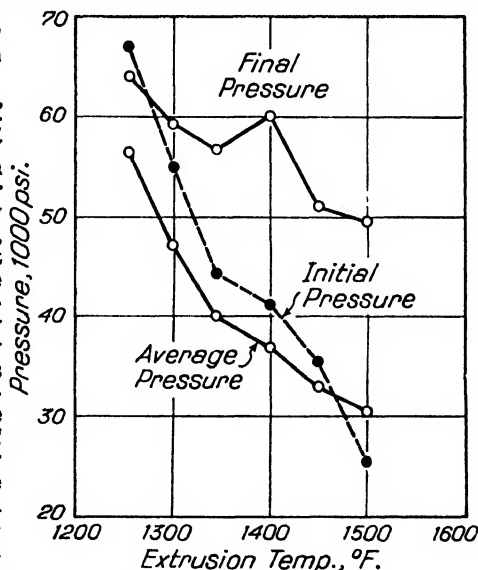


Fig. 2—Effect of temperature and pressure in extruding free cutting copper alloy through a two-hole die 0.65 in. in dia.

Table I
Copper-Base Extruded Alloys—Rod

Alloy	Cu	Pb	Sn	Ni	Mn	Al	Misc.	Temp. Range for Extrusion, °F.	Mechanical Prop. ¹ As Extruded, Tensile, Psi.	Elong., % in 2 in.	Commonly Used Temper	Mechanical Prop. ¹ For Such Temper, Tensile, Psi.	Elong., % in 2 in.
Free cutting brass.....	61.5	3.5						1300-1400	48,000	45	Drawn	55,000	30
Forging brass.....	60	1.75						1250-1350	50,000	45	As extruded	50,000	45
Architectural bronze.....	58	3						1200-1300	54,000	45	As extruded	54,000	45
Naval brass.....	60		0.75					1200-1350	55,000	45	{Light Drawn {Hard Drawn	63,000 70,000	35 25
Free cutting Naval brass	60	1.5	0.75					1200-1350	55,000	45	{Light Drawn {Hard Drawn	63,000 70,000	35 25
Manganese bronze.....	57.5		1		0.05		1 Fe	1150-1300	65,000	35	Drawn	80,000	20
Muntz metal.....	59							1250-1350	52,000	45	Drawn	62,000	30
Rivet metal.....	63							1300-1400	46,000	50	{Rivet Temper {Hard Drawn	60,000 80,000	35 10
Free cutting commercial bronze	89	2						1400-1500	36,000	50	Drawn	45,000	30
Copper ²	100							1500-1650	32,000	40	Drawn	42,000	25
Leaded copper.....	99	1						1500-1650	32,000	40	Drawn	42,000	25
Silicon bronze ³	96						3 Si	1450-1550	53,000	70	{Drawn half hard {Drawn hard {Drawn extra hard	73,000 90,000 108,000	45 35 25
10% Nickel silver.....	45	2		1.0	0.5			1300-1400	80,000	10	As extruded	80,000	10
13% Nickel silver.....	41	1.25		1.3	0.5			1300-1400	90,000	7	As extruded	90,000	7
Nickel-aluminum bronze..	91					1.5		1400-1500	50,000	45	Quenched & aged	100,000	20
Nickel-aluminum bronze..	85			12.5		2.5		1600-1700	60,000	35	Quenched & aged	125,000	10
Aluminum bronze 5%.....	95					5		1500-1600	50,000	60	Drawn	70,000	30
Aluminum bronze 8%.....	92					8		1350-1450	60,000	60	As extruded	60,000	60

¹Properties shown are average; not to be used as minimum requirements.

²Balance in all cases is zinc.

³Includes all types of copper.

⁴Analysis is typical of all 3% silicon bronzes.

few are ordinarily employed for the production of extruded products. The commercial designations and nominal composition of these are shown in Table III.

Table II
Copper-Base Extruded Alloys—Tube

Alloy	Approximate Composition					Temp. Range for Extrusion, °F.	Approx. Mech. Properties			
	Cu						As Extruded Tensile, Psi.	Elong., % in 2 in.	After Final Anneal Tensile, Psi.	After Final Anneal Elong., % in 2 in.
High brass	66.5			0.5	33	1225-1275	45,000	65	50,000	55
Admiralty brass	70		1		29	1200-1250	46,000	65	52,000	60
Red brass	85				15	1425-1475	38,000	50	44,000	42
Aluminum brass	78		2		22	1350-1400	48,000	65	52,000	60
Nickel silver 18% ...	65	18			17	1800-1850	55,000	45	60,000	40
20% Cupro-nickel ...	75	20			5	1800-1850	48,000	40	53,000	35
30% Cupro-nickel ...	70	30				1850-1900	54,000	35	63,000	30
Silicon bronze	96		3Si		1	1350-1400	53,000	65	60,000	60
Nickel-aluminum bronze	92	4	4			1500-1550	50,000	45	60,000	30
Aluminum bronze ...	95		5			1475-1525	50,000	55	58,000	35

*Properties shown are average, not to be used as minimum requirements.

Table III

Designation	Cu	Si	Mn	Mg	Cr
2S	(99 Min. Aluminum)				
3S			1.25		
51S		1.0		0.6	
53S		0.7		1.25	0.25
A17S	2.5			0.3	
17S	4.0		0.5	0.5	
24S	4.2		0.5	1.5	

The relative ease of extrusion of these alloys is approximately in the order listed, the first being the most readily worked.

Alloys 2S and 3S are subject to strain hardening only and can, therefore, be produced only in the annealed or as extruded tempers. The remaining alloys can be produced in the same two tempers and in addition, heat treated tempers. In all cases the extrusion temperature ranges from about 700-950°F. and velocities varying from about 5-300 ft. per min., depending on the size, shape and alloy.

Even though the annealed and as-extruded tempers of the heat treatable alloys are commercially available, all of these except 53S are generally used only in the heat treated tempers in order to secure the maximum mechanical properties and maximum corrosion resistance. Alloy 53S has essentially the same corrosion resistance in all tempers.

The aluminum alloys are subject to the same extrusion defect as are the brasses.

Hot Extrusion of Magnesium-Base Alloys—The magnesium-base alloys are of relatively recent introduction but for certain applications have already gained fairly wide acceptance. Several of the magnesium-base alloys are commercially extruded, using equipment essentially the same as that for copper-base or aluminum-base alloys.

As a class, magnesium alloys are quite hot short as compared to other alloys already dealt with. Therefore, only a narrow range of temperature is permissible and the extrusion rate is low as compared to that employed in the brasses. Commercially, speeds of approximately 2-12 ft. per min. are used.

Normally the temperatures are maintained between 600-800°F. for any of the magnesium alloys, the higher temperature being best for producing thin sections and the lower temperature for relatively heavier sections. The physical properties are somewhat affected by temperature, being decidedly better at the low temperature due to greater grain refinement.

In Table IV are given the properties of four alloys which can be extruded commercially.

In most commercial work the temperature and speed of extrusion is such that the pressure on the metal during the extrusion is between 40,000 and 60,000 psi. The starting pressure is naturally somewhat higher than this and is greatly dependent on the temperature.

Table IV
Extruded Magnesium Alloys

Alloy	Aluminum	Manganese	Zinc	Magnesium	Approximate Tensile, Psi.	Approximate Elongation, % in 2 In.
A	8.0	0.2	....	Remainder	47,000	13
F	4.0	0.3	....	Remainder	40,000	16
J	6.5	0.2	0.75	Remainder	43,000	18
M	...	1.5	....	Remainder	42,000	7

These alloys are particularly useful where advantage can be taken of their extreme lightness. For parts that have to be stopped and started very rapidly, the low specific gravity of 1.8 typical of these extruded materials is decidedly advantageous. Another advantage is their excellent machinability.

Hot Extrusion of Zinc-Base Alloys—The hot extrusion of zinc and zinc alloys has not been commercialized to any large extent because of the expense of the process. The expense lies in the greater extrusion pressure necessary than with brass and aluminum and the lower extrusion speed caused by the tendency of zinc and zinc alloys to check and crack as the extrusion speed and consequently the temperature build up.

High grade zinc has been extruded at speeds up to 75 ft. per min. The extrusion pressure approached 100,000 psi. initially. This material had ultimate tensile strengths of 14,500-20,500 psi. and elongations in 2 in. sections of 5-26% depending upon impurity content.

The zinc alloys containing copper or copper and magnesium show strengths up to 32,000 psi. and elongations of 3-7%, but the extrusion speeds decrease to 12 ft. per min. on $\frac{1}{2}$ in. dia. rod and the extrusion pressures run up to 120,000 psi. In extruding these alloys, the billets must be preheated to 520-570°F. and the container to 660°F. in order to start the extrusion.

Hot Extrusion of Nickel Alloys and Stainless Steel—Considerable experimental work has been carried out on the high melting point alloys but only recently has any commercial application been made. There is at present one installation where stainless steel tubing is being produced in commercial quantities using a 2,000 ton press. There is another installation using a 600 ton vertical press now commercially extruding nickel, Monel metal, and similar alloys. The basic difficulty is that several of the outstanding properties of these alloys are precisely those which intensify the difficulties of extrusion. Their great mechanical strength at high temperature and considerable resistance to deformation particularly militate against their production by extrusion methods.

Of course, several copper-base alloys containing considerable amounts of nickel are regularly produced in quantities but these are not looked upon as nickel alloys, being referred to in the section on copper-base alloys.

Cold Extrusion—Hooker Process—In the Hooker process relatively heavy walled cup shaped blanks are extruded at high speeds, using ordinary crank presses instead of the usual extrusion press. This operation differs essentially from the hot extrusion in two important respects. First, the metal is invariably fed into the press at room temperature and there is little, if any, rise in temperature during the process. At least the temperature of the metal remains well below that of incipient recrystallization so that a hard worked structure and corresponding properties result. Second, the process is carried out at relatively high velocities and on relatively small masses of metal. The Hooker process is commercially applied to two classes of products; first, small arms cartridge cases, and second, small thin walled seamless tubes.

In Fig. 3 there are shown four steps in the making of a small brass cartridge case. The alloy used is high grade 70-30 or cartridge brass. The first two steps comprise a cut-and-draw and a redraw, each performed in the ordinary manner on a plunger press. The third and fourth operations illustrate the application of the Hooker process. The two sectional illustrations show the position of the tools and the metal just at the start of and near the finish of the application of the Hooker process. It will be seen that with the application of pressure by the shoulder of the punch,

the metal is made to flow (extruded) through the restricted annular space between the punch and the opening in the bottom of the die.

This process is well adapted in general to small tubular articles in copper or aluminum where a large number of the same size piece are to be made. For instance, in 70-30 brass cartridge cases, this procedure is justified in competition with the ordinary drawing procedure on runs of approximately 10-15 million pieces. In the making of these cartridge cases, extremely high tool pressures are encountered, naturally resulting in considerable wear on the dies and punches.

In the manufacture of copper tubes, the sizes which are found economical, run from about $\frac{1}{8}$ in. O. D. to approximately $\frac{3}{8}$ in. but as yet not in commercial production. The wall thicknesses usually will vary from 0.004 to about 0.010 in. Anything less than about 0.004 in. is not commercial as it causes excessive tool breakage, and tubes with wall thicknesses over 0.010 in. can be produced at less cost by other methods. The length extruded is usually about 8-12 in. and the maximum feasible length about 14 in.

Although any type of copper probably could be used, oxygen-free copper is the one actually most employed. This, of course, is a homogeneous soft material, well adapted to this operation.

In the sizes ordinarily made the actual velocity of extrusion is much higher than ever attained in the ordinary hot extrusion of either rod or tubes on hydraulic presses. The actual working stroke consumes but a small fraction of a second and velocities through the die as high as about 2000 ft. per min. are attained. This is so rapid that there is little temperature rise in the die and the material itself is heated only slightly. The metal is severely cold worked and quite high strengths are found in the finished tubes. These may run from about 50,000-60,000 psi. in copper.

The Hooker process also is used in making a considerable range of small seamless aluminum tubes. Like copper, the aluminum is severely cold worked in this process but the extruded tube may be softened by suitable annealing subsequent to the extrusion.

Impact Extrusion—This process is somewhat similar to the Hooker process but differs from it in some fundamental respects. Whereas in the Hooker process the metal is extruded ahead of the punch through an annular orifice between the die and the punch, the flow of metal in the impact process is in the reverse direction. Here a solid bottom die is used and a flat slug of metal in place of the cup shaped slug of the Hooker process. Here also the punch has no shoulder and when the pressure is applied by the end of the punch to the flat slug, the metal flows back up over the punch. This process is sometimes erroneously referred to as the Hooker process and also sometimes by the misleading term "cold drawing." The term "impact extrusion" seems to be the more logical one to use.

In the making of flat bottom cans or cups of all types, this process frequently competes with similar shells drawn from sheet metal. The relation between the lengths and diameters of the can largely determines which process is the more economical. Relatively shallow articles are cheaper to produce by drawing but with increasing length the advantage swings toward the impact extrusion process. The impact extrusion process is applied to the making of various aluminum articles.

Shells or cups up to approximately 10 in. in length are found well suited to this process. The diameters may vary $\frac{1}{2}$ in. to about 4 in., and the wall thicknesses from about 0.003 in. to about 0.045 in. In general the wall thickness is more or less in proportion to the diameter of the tube or cup.

This process is also applied to making an enormous quantity of collapsible tubes such as used for tooth paste, paint pigments, and shaving creams, using pure tin or lead or tin-lead alloys. The pure tin is required for foodstuffs or materials for human consumption, but the lead alloys are found suitable and are naturally less expensive for containers for other types of products.

A great deal of zinc is extruded by this process, using blanks from $\frac{1}{4}$ -2 in. dia. and $\frac{1}{16}$ - $\frac{3}{8}$ in. thick. The dia. of the slug or blank usually equals the outside dia. of the finished cup, and a sufficient thickness is used to provide the desired length

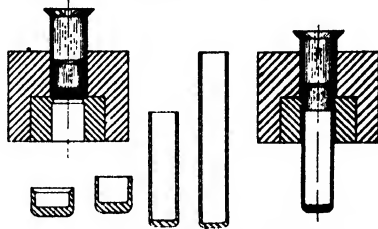


Fig. 3—Diagrammatic sketch showing the steps in making a small brass cartridge case by the Hooker process.

at required wall thickness. In the application of the process to zinc, it is desirable to start with metal having a random orientation or at least a structure such that the blank has no directional properties. Otherwise the tops would be uneven, resulting in distortion of the side walls and causing an excessive loss in trimming. It is customary with zinc to heat blanks to a temperature of 390-480°F. in order to reduce the pressure required. It has been found that with common zinc a pressure of 87,000 psi. is required at 300°F. and 40,000 psi. at 480°F.

Forging by the Blacksmith

By William Telfer*

When selecting the material of the correct dimensions, the blacksmith first must decide how the part is to be forged. One procedure would be to select stock a little larger than the largest dimension and obtain the smaller dimension by drawing down. If the forging is to be short, stock comparable with the smaller dimensions could be used, and the larger dimensions could be obtained by upsetting. In either case it would be correct procedure to figure the approximate cubic contents or weight of the finished forging before selecting the stock, and allow enough for squaring up the end, and for loss due to scaling. The loss due to scaling varies with the number of reheatings and with the atmosphere and temperature of heating.

Blacksmith Tools—The tools used at the anvil with hand hammers or sledge hammers are swages, fullers, set hammers, flatters, punches and chisels with tongs to hold the work. The swages, fullers, set hammers and flatters are usually made of 0.70-0.80% carbon steel, and the hot and cold chisels of 0.80-0.90% carbon steel. A 0.45-0.50% carbon steel could be used for the bottom fuller and swage which fit in the square hole of the anvil. Cast medium carbon steel or a good gray iron will answer the purpose for the swage block.

Fullers—When shoulders are required on both sides of the forging, it is worked between the top and bottom fullers, the top being struck with a sledge. The top fuller is often used alone to make depressions on one side of the forging as it lies flat on the anvil. The radius of the depression or fillet will determine the size of the fullers to be used. Fig. 1 shows a top and bottom fuller.

Swages—These tools (Fig. 2) are used for finishing round or semi round work at the anvil after it has been drawn nearly to size by the use of either the hand hammer, sledge, or power hammer.

The depth of the impression should be about one third the diameter of the part of the forging to be swaged, and the edges should be well rounded. If the bottom swage is made to come flush with one or both sides of the anvil, it will have a greater range of usefulness.

Set Hammer and Flatter—Both are used on flat surfaces, but if necessary to work on square shoulders or in depressions which are too small for the flatter, the set hammer usually answers the purpose. The set hammer and flatter are both shown in Fig. 3.

Cold Chisel—Some steels in the hot or cold worked condition can be notched all

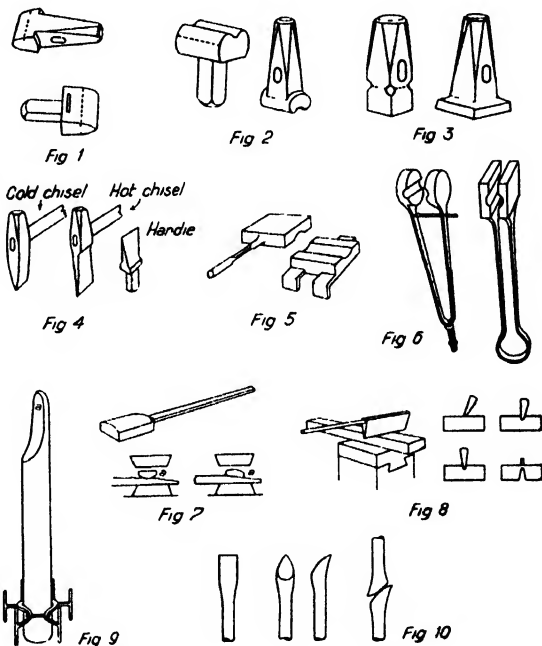


Fig. 1—Top and bottom fuller.

Fig. 2—Swages.

Fig. 3—Set hammer and flatter.

Fig. 4—Cold chisel, hot chisel, and handle.

Fig. 5 and 6—Power hammer swages.

Fig. 7—Power hammer fuller.

Fig. 8—Power hammer cutters.

Fig. 9—Stocks for turning forgings.

Fig. 10—Scarfing operations for lap welding.

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or part way around by the use of this chisel and a sledge, and then broken by a sharp blow (Fig. 4).

Hot Chisel—This is much thinner than the cold chisel (Fig. 4), and is used on steel at increased temperatures. The cut is usually made all the way through.

Hardie—This tool should fit in the square hole in the anvil. It can be used on some steels both hot and cold. The metal is placed on the hardie and struck with a hand hammer (Fig. 4).

When belt, air or steam hammers are used the tools are somewhat similar to those used for sledge hammering but modified to permit their use with power hammers.

Power Hammer Swages—Swages are usually made of 0.45-0.50% carbon steel, and the shape is obtained by sinking hot either by the use of a round bar or some special shape. Most of the work done by swaging is round in cross section, but special shapes can be produced by the use of these tools. Where the forgings are of a large diameter, the top and bottom swages are usually not attached by spring handles because of the weight to be handled by the helper. Fig. 5 and 6 show the hammer swages.

Power Hammer Fuller—The hammer fuller shown in Fig. 7 is used for drawing short sections where the dies are too wide, and also for forging a taper. The rounded side of the fuller is used for breaking down or roughing, and the flat side could be called a "flatter" for finishing.

Power Hammer Cutters—Hot cutters (Fig. 8) usually consist of a straight blade with a handle about 3-8 ft. long depending on the size of the forging. Some are made with curved blades and others form an angle of 90°. The handle near the blade should be flat so as to act as a spring and prevent injury to the wrists or arms of the blacksmith.

Stocks—These are used for turning and handling the forgings at the hammer. Fig. 9 shows how they are used.

When the quantity of forgings of the same kind justify the making of dies, the blacksmith first makes one forging, taking special care with the shape and dimensions. This sample or master forging then is made use of to sink the die or dies. The die blanks are usually forged with handles drawn out. The next step would be to heat the blanks to a high temperature, and put the master in between, and then force them together by the use of heavy blows. Sometimes the dies are partly sunk before using the master forging. These dies or swages, as they are sometimes called, are held in line by spring handles or guide pins, or both, and held on the bottom hammer die by the helper. The smith has used this method of increasing production for many years. It has been used for some time, but on a much larger scale, by the producers of drop forgings.

Forge Fire—A cast iron hearth with a bowl or depression in the center for the fire, and an opening in the bottom for the tuyeres will answer the purpose for light work. For heavy work an inexpensive forge can be constructed from $\frac{1}{2}$ in. steel plate formed into a square or a cylinder about 4 ft. in dia. and 2 ft. 6 in. in height. Space below the tuyere can be filled with broken brick and ashes. The distance between the top of the hearth and the tuyere should be about 10 in. for heavy, and about 4 in. for light work. Provisions should be made for removing ashes from below the tuyere. The clinkers can be removed from above. After starting the fire, wet coal is banked on both sides, this not only supplies coke for surrounding the metal to be heated, but acts somewhat like the fire brick wall of a furnace.

The object is to heat the steel uniformly to high temperature with as little oxidation as possible. This can be accomplished by keeping a good bed of coke between the tuyere and the steel to consume the oxygen in the blast, and a good covering is necessary. Better control of the atmosphere and the temperature can be obtained in a furnace, but in a forge fire, the heat can be concentrated at some given point of the bar or forging.

On building a forge fire for medium and heavy work, a block of wood corresponding to the size of the fire required is placed on the tuyere, and wet coal is firmly packed around it to the depth required. Two boards are then used as forms to build the banks to the length and height required.

The fire is started by shoveling hot coke into the hole left after the wood is removed. The banks usually stand undisturbed for a half to a whole day, and hard coke broken to a convenient size is used as a fuel.

The banks of coal coke to the depth of several inches during the day and this coke is used along with the hard coke on the following day, after the fire is rebuilt.

Fine coal is more desirable for forge fires, as it packs much better when wet than coal consisting of lumps. A good grade of bituminous coal, low in ash and sulphur, high in fixed carbon, and good coking qualities, is usually the fuel for the forge.

Hammer Size—During the forging of the steel, the size will determine the method of applying the force. If the temperature is close to the upper limit of the plastic range, a 1½ lb. hammer would supply enough force for ¾ in. dia. low carbon and ½ in. high carbon steel, and a 14 lb. sledge would answer the purpose up to 1½ in. low carbon steel. Of course, if the smith has access to a power hammer, time would be saved by using it.

Precautions in Heating and Forging Steel—Too rapid heating will cause uneven expansion of the metal, starting internal cracks. This is especially dangerous in high-carbon and high-alloy steels. When such steels have to be heated near the upper limit of the plastic range, it would be advisable to use a preheat furnace at temperatures between 1,200 and 1,400°F., depending upon the composition, size, and previous treatment.

Forging temperatures too high for the amount of work to be done will result in large grains in the finished forging. Excessively high temperatures used might be in the melting range, and when forged, will cause voids and oxide inclusions. This is commonly called burning.

Not enough force applied will cause a rupturing of the steel by working the outer layers beyond the inside metal. Sufficient force should be applied to affect the whole cross section, and this should be continued until close to the finished forging dimensions.

Continuing the forging at temperatures too low will leave the steel in a highly stressed state, and, if not followed by some form of heat treatment, will result in short life for the machine part.

When a great reduction in size is necessary, the steel should be forged down on the square or rectangular shape. The stock should be turned so that the sides will form an angle of 90°. If the finished cross section is to be round, forging should be continued on the square until close to the finished dimension. The corners can then be forged to produce an octagonal shape, and little rolling is necessary to finish.

If the above procedure is not carried out, the metal might be in shear some of the time, instead of compression, and if the steel is slightly rigid due to low temperatures or a hard alloy steel, such as high speed steel, it will be ruptured.

Overlapping of the steel, forming cold shuts, is often caused by using hammer dies and tools with sharp corners.

The above applies to both forging on the anvil using a hand hammer and forging between the flat dies of a power hammer or press.

Welding at the Forge—When wrought iron or steel is heated to high temperatures, such as used in welding, and are exposed to the air, they oxidize rapidly. To secure a good bond between two pieces, this oxide must be so fluid that it can be squeezed out from between the surfaces. The fusion point of the oxide is lowered by the use of fluxes.

Clean silica sand and borax are two common fluxes used at the forge. Borax, having a comparatively low fusion point, is used on high carbon steel. It can be placed on the steel at low temperatures, after "scarfing," consequently supplying a protective coating. Also, it can be sprinkled on the steel while heating. It might be said it serves a double purpose, lowering the fusion point of the oxide, and preventing further oxidation.

Sand has a high fusion temperature, but when combined with iron oxide it becomes fusible at lower temperatures. It is generally sprinkled on the metal when close to the welding temperature.

Silica sand is cheaper than borax and can be used on the low carbon steels. Fluxes are not necessary in forge welding of wrought iron and very low carbon steel, because it is possible to melt the oxide without burning or melting the metal.

The operation of preparing the pieces for welding is known as "scarfing." Fig. 10 shows the shape used in lap welding. Other types of welds are known as butt, V or split, T, corner, and jump.

Precautions in Forge Welding—Before shaping the "scarfs" upset the end of the pieces to be welded sufficiently, and far enough back from the "scarf" to allow for enough mechanical working during and after welding.

The grain size of the metal in the weld and adjacent to the weld will depend on the amount of work it receives and the finishing temperature.

The "scarf" surfaces should be well rounded so that contact will be made in the center. The curved surfaces will force the liquid oxide or dirt out from between.

Guard against excessive oxidation on heating by keeping a good supply of coke in the bottom of the fire, and have the metal well covered with fuel. The scarfed ends should be face down in the fire.

When up to the welding temperature, enough speed should be used to get the pieces together before the oxide solidifies.

Blows should be heavy enough to work the metal uniformly, using a power hammer when necessary.

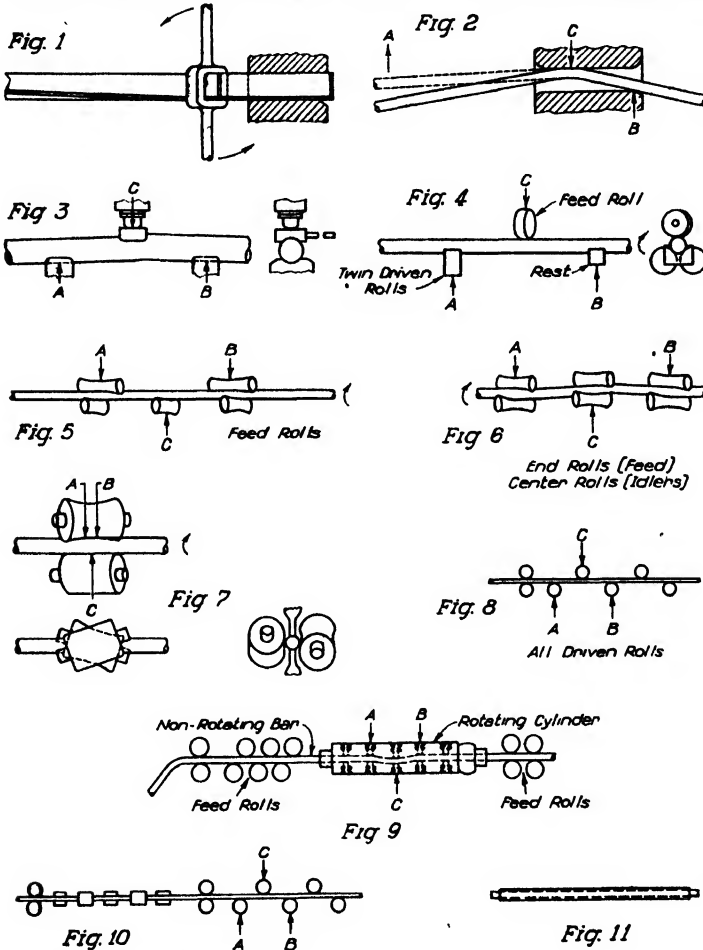
The metal in and adjacent to the weld may be annealed to produce a more homogeneous structure, and consequently obtain greater ductility, which usually is low in forge welds.

The properties of a forge weld will depend on the following factors: (1) The skill of the welder; (2) The weldability of the material; (3) The fuel used—sulphur and ash will interfere; (4) The amount of flux used and the time of application; (5) Uniformity of temperatures of pieces to be welded; (6) Atmospheric condition of the fire or furnace; (7) Amount of oxide or fuel ash trapped in between the "scarfs"; (8) Method of working—too much rolling on the anvil or between the dies of a power hammer when welding round stock will be detrimental, and (9) Force of the blow.

Straightening Bars, Shapes and Tubing

By J. D. Armour*

Many types of straightening devices have been developed for straightening bars, shapes and tubes from the simple hand straightening to very complicated straightening machines. However, the fundamental principle involved in all of these straightening methods except twisting and straightening by stretching is the same. This principle may be explained by referring to Fig. 3. The bar is supported at points A and B with the convex side of the bow or kink toward point C. Sufficient pressure is applied at C to cause the bar to become bowed in the opposite direction. The pressure must be sufficient to exceed the elastic limit of the material and set up just sufficient strain in the bar to allow it to return to the straight position but



- Fig. 1—Hand twist straightener.
- Fig. 2—Hand straightener.
- Fig. 3—Punch straightener.
- Fig. 4—Rotary straightener.
- Fig. 5—Five roll rotary type straightener.
- Fig. 6—Six roll rotary type straightener.
- Fig. 7—Two roll rotary type straightener.
- Fig. 8—Flat, square, and hexagon bar straightener.
- Fig. 9—Wire straightener.
- Fig. 10—Horizontal and vertical straightener for flat, square, and hexagon wire and bars.
- Fig. 11—Straightening by stretching.

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no farther when the pressure is released. The greater the bow in the bar and the higher its elastic limit the greater the pressure required to produce the correct amount of strain. To straighten a bar by this method, the material must possess the property of resilience, it must be capable of cold deformation, and it must strain harden. In the diagrams, Fig. 2-10 inclusive, the arrows show the location of the points corresponding to points A, B and C of Fig. 3. As mentioned above, this same principle applies in all of the bar straightening methods except twisting and straightening by stretching.

In straightening to remove twist, the bar is twisted in the opposite direction until the elastic limit is exceeded and just sufficient strain set up to allow the bar to return to the straight position but no farther.

In straightening by stretching, the bar must be stretched until the elastic limit is exceeded and sufficient strain set up to prevent the bar from returning to its original position. The bar must be permanently elongated and reduced in cross section to remain straight after the stress is removed.

Hand Straightening—While many mechanical methods have been developed for straightening bars and shapes, the original method of hand straightening is still used extensively on jobs where great accuracy and precision are required or where odd shapes make mechanical straightening impractical.

For accuracy and precision, surface tables and wooden mallets are used while, for odd shapes, grooved wooden blocks as illustrated in Fig. 1 and 2 are used. Hand straightening requires great skill on the part of the operator and it sometimes requires several years for an operator to acquire sufficient skill to do particular jobs of hand straightening.

Punch and Press Straightening—Punch and press straightening are semimechanical methods, the principle of which is illustrated in Fig. 3. The operator usually locates a kink or bow in round bars by holding a piece of chalk close to the surface of the bar and then rotating the bar so that any high spots will be marked by the chalk. The high spot is then brought under the ram of the straightening press and sufficient pressure applied to take out the kink or bow. In the case of shapes other than rounds, the out-of-straight condition must be detected by eye or with the aid of a straight edge. The type of straightening requires considerable skill on the part of the operator. A straightening press is sometimes referred to as a gag press and the straightening operation as "gagging."

Rotary Straightening—Rotary straighteners are straighteners in which the bar is rotated at the same time it is fed into the straightening machine and are necessarily confined to straightening round bars. The simplest form of rotary straightener is illustrated in Fig. 4. The top roll can be set at any desired angle which controls the speed of the bar. It can also be adjusted up and down to control the pressure of the bar. It can readily be seen by referring to Fig. 4 that the same principle of straightening is involved here as for punch or press straightening.

Fig. 5, 6 and 7 show diagrammatically other popular types of rotary straightening machines. While they are more complicated in design than the simple rotary straightener to obtain such features as speed or polishing effect, they nevertheless involve the same straightening principle as can readily be seen by a little study of the illustration.

Fig. 8 illustrates the principle of a straightening machine used for flats, squares and hexagons. It will be seen that as the bar passes through the machine it is subjected to a double straightening action similar to that employed in Fig. 3. In some straighteners for these shapes, both horizontal and vertical rolls are used which give a setup similar to that shown in Fig. 10 for wire.

Wire Straightening—Fig. 9 shows the type of straightening machine used for straightening coiled round wire into straight bars. In this case, the wire does not rotate as it feeds through the machine. A cylinder with adjustable dies rotates around the wire and produces the straightening action. Some straightening is also provided by the feed rolls on the entering end as will be seen from the illustration.

Fig. 10 illustrates the setup for a wire straightener for shapes other than rounds. It amounts to a double setup similar to Fig. 8, one horizontal and one vertical, so that the wire will be straightened in both directions with one pass through the machine.

Stretching—Fig. 11 shows how a bar must be changed in size to be straightened by stretching. The change of shape is of necessity exaggerated in the illustration as the increase in length and decrease in cross section need actually be very slight to produce the required effect. This method is well adapted to straightening odd shapes.

Flattening of Mild Steel Sheet and Strip

By R. S. Burns*

Sheets are ordinarily sold in two grades of flatness: (1) commercial flatness, in which the sheets are to be severely drawn, and hence, the original flatness does not have much effect on the shape of the drawn article; and (2) stretcher level flatness, in which the sheets are used for panel work where little forming is done on the sheet, and the finished product is desired flat and free from buckles.

Simply because sheets are flat before moderate forming does not necessarily mean that they will be flat after fabrication, unless care is taken by the fabricator to insure that buckles are not thrown into the sheets during forming.

Commercial flatness can ordinarily be produced on a roller leveler or cold rolls, but where it is required that sheets be very flat, producers must resort to stretcher leveling. For the most part, steel sheets are flattened as a final operation before shipping; however, there are instances where measures are taken to flatten sheets as an intermediate operation, in which case the flattening is done both to improve the flatness of the finished product and also to aid in the performance of succeeding operations.

The normal flatness varies somewhat according to the grade; and as a rule the lighter the gage and the wider the sheet, the less flat the sheets will naturally run.

The permissible variations in flatness for commercial cold rolled and stretcher leveled sheets as set up by the Association of American Steel Manufacturers Technical Committees are as follows:

Ordered Gage (U.S.S. Ga. No.)	Ordered Width, in.	Max. Height of Buckles, in.
2 to 11, incl.....	48 or under	$\frac{3}{8}$
	Over 48 to 60 incl.	$\frac{3}{4}$
	Over 60 to 72 incl.	1
	Over 72	$1\frac{1}{4}$
12 to 16, incl.....	48 or under	$\frac{3}{8}$
	Over 48 to 60 incl.	1
	Over 60 to 72 incl.	$1\frac{1}{4}$
	Over 72	$1\frac{1}{2}$
17 to 30, incl.....	36 or under	$\frac{3}{8}$
	Over 36 to 48 incl.	1
	Over 48 to 60 incl.	$1\frac{1}{4}$
	Over 60	$1\frac{1}{2}$

For stretcher leveled sheets, 22 gage or heavier, the height of buckles of a sheet lying on a flat surface shall not exceed $\frac{1}{4}$ in. This permissible variation cannot be assured for sheets lighter than 22 gage.

The permissible maximum height of buckles given for stretcher leveled sheets and for sheets not stretcher leveled applies to not more than two buckles on a side or in the middle of the sheet.

Roller Leveling—A roller leveling machine consists of two sets of several horizontal small diameter rolls held in a housing and so arranged that the top and bottom rows are offset, permitting the rollers to mesh. The upper and lower rolls are so staggered or meshed that the sheet passing through the leveler is flexed alternately up and down (Fig. 1). This has the effect of cold working the surfaces more than the interior of the sheet. The layers of rollers are movable with respect to each other; so that by means of a screwdown the rollers may be made to mesh more or less as desired, thus controlling the pressure exerted on the piece during the operation. On levelers with the proper amount of staggering of the rolls, flatness may be obtained with essentially no increase in length of the sheet. At the entrance side of the leveler, the axes of the bottom and top rolls are closer together than at the exit side. This results in heavier flexing in passing through the earlier rolls of the machine. At the exit side the action is chiefly that of straightening. Sheets are ordinarily passed through the roller leveler one at a time; however, in some cases several may be passed through at a time, depending on the thickness.

Hot roller leveling is usually a part of the treatment for hot rolled sheets and plates over .060 in. in thickness. This has the effect of removing much of the distortion caused by hot rolling and open annealing. When roller leveling hot, it is not necessary to temper pass material before leveling to prevent breaks or fluting.

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However, before it is possible to cold roller level a dead soft annealed sheet, the sheet must receive a pass on the temper mill to minimize the yield point elongation, and hence, prevent "roller level breaks" or fluting as the sheet is bent around the rolls.

With the advent of wider and thinner cold rolled sheets, roller leveler manufacturers have resorted to machines with small roll diameter. To get the same amount of stress in the extreme fibers of a sheet, it is necessary to bend the lighter gage sheet around a smaller diameter roll. With the use of small diameter rolls in the leveler, it has become necessary to back the rolls up with rolls of larger diameter to decrease the flexing of the roll when pressure is applied. Then, too, with the recent developments in high tensile steels, it has been found that these sheets cannot be flattened on the ordinary leveler but must be run on the leveler with small rolls in order to create a stress high enough to get the necessary deformation. Roller levelers are not ordinarily used to eliminate the tendency to stretcher strain unless the sheet has first been temper rolled. Sometimes if the sheets are unused for a period long enough to cause an appreciable return of the yield point of elongation due to aging, the tendency of the sheet to stretcher strain may be eliminated, for a short time, by roller leveling immediately before drawing. In this case the roller leveling is not done as a flattening operation but is done to prevent stretcher strain during drawing.

Roller level corrugations or chatter, consisting of small waves running across the sheet, constitute the main defect caused by this operation. Ordinarily this defect occurs because the leveler is not properly adjusted for the gage of the sheet being leveled, or when the sheets are badly buckled before roller leveling takes place. Roller leveling is only a semieffectual means for flattening sheets, and sheets having a full center are easier to flatten by roller leveling than sheets with long or wavy edges. It is a relatively inexpensive operation, and sheets of commercial flatness can readily be produced.

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Stretcher Leveling—Stretcher leveling is a positive means of producing flatness in finished sheets, if the sheets have been properly processed for good flatness in stretcher leveled sheets. In this operation sheets are gripped on each end by jaws attached to pistons which are forced apart slowly by hydraulic pressure (Fig. 2). The number of sheets stretched at one time depends on the gage. However, it is rare that more than two sheets are stretched at one time, because the grips do not hold tightly enough to stretch the center sheets. The effect produced is actually one of stretching the sheet gradually, taking up all the slack which may exist in the form of waves or buckles, continuing until the sheet is stretched taut and its shape is practically a flat plane. The stretching proceeds, theoretically, past the elastic limit of the steel, being in the neighborhood of 1-2% elongation, so that the sheet will not spring back into its original shape but will spring back uniformly across its full width and remain flat. This means that the sheet takes a permanent set in its flat condition, which shape is not materially altered when stretching is stopped and the sheet is removed from the grips.

For stretcher leveling, it is obvious that sheets must be soft and ductile and have an elastic limit low enough to permit them to take a permanent set with a pull which is within the limit of the stretching machine. Dead soft sheets are not usually stretcher leveled without first giving them a temper pass on the cold mill. Unless sheets are given a temper pass prior to stretcher leveling they have a

Fig. 1

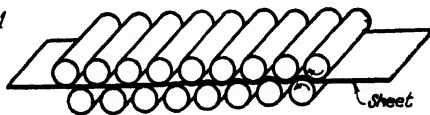


Fig. 2

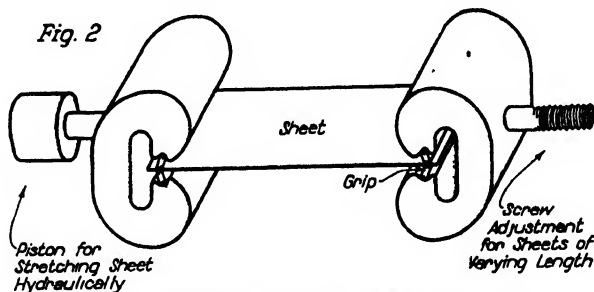


Fig. 1—Diagrammatic sketch of a roller leveler.

Fig. 2—Diagrammatic sketch of a stretcher leveler.

tendency to stretcher strain when stretcher leveled and even if the stretching proceeds far enough to pull through the stretcher strain, strain markings are left on the sheet and are undesirable for many applications.

Material that has a variation in physical properties across the sheet usually does not stretcher level satisfactorily. The differences in unit stress produce variation in strain, within the elastic range, across the sheet, with the result that release of the load produces different amounts of elastic contraction which causes nonflatness.

Nonuniformity in gage across a sheet of material frequently gives trouble in stretcher leveling. This is due to difficulties in obtaining perfect gripping. Slippage in the grips will produce different unit stresses in different parts of the sheet. If this slippage is high enough so that stretching is not carried definitely beyond the yield point in all parts of the material, varying amounts of elastic contraction will result upon release of load, which in turn produces nonflatness.

As the physical properties of sheet material increase, the leveling operation becomes more difficult because of the greater elastic contraction upon release of load, as well as greater difficulties in obtaining perfect gripping in the leveler.

In stretcher leveling light gage sheets (.031 in. and thinner) the difficulties are greatly increased, owing to inability to elongate the sheets sufficiently to flatten them without producing cross breaks or buckles parallel to the direction of stretch.

Cold Drawing Steel Wire

By E. E. Legge*

Wire is ordinarily thought of as consisting of long circular sections. Yet it may have any one of an infinite number of cross sectional shapes. The most common shapes are circular, square, hexagonal, octagonal, oval, half-oval, half-circular, triangular, and flat or rectangular. In general, wire consists of innumerable products shaped by pulling metal through a die.

The limits of wire drawing range from .001 in. to approximately 1 in. Wire is classified with respect to size as coarse wire—coarser than No. 20 (.035) gage—and fine wire (No. 20 gage and finer).

Historical—Iron wire was first manufactured in Bavaria, in the middle of the fifteenth century. In America, the first steel wire was drawn by Nathaniel Miles, in 1775. Later, in 1831, Ichabod Washburn and Benjamin Goddard drew steel wire in Northville, now Worcester, Mass.

General Description of Process—The process of drawing steel wire begins with a hot rolled rod in coil form, weighing from one hundred to six hundred pounds, depending upon the type of rod mill used and the quality of rod surface desired.

The wire requirements determine whether Bessemer, acid or basic open hearth, or electric steel should be used. Special alloying elements are rarely used except for the larger sizes of wire because alloys are not required in small sections to produce a uniform heat treatment throughout the entire cross section. Combinations of cold working and heat treating of rods and process wire make it possible to develop a wide range of physical properties which will meet almost every demand likely to be made upon steel wire.

The range of analysis of plain carbon steel is carbon 0.05-1.30%, manganese 0.15-1.65% with the other elements normal for the type of steel.

Most wire is drawn dry, with adequate lubricants; however, fine sizes and special finishes are drawn by the so-called wet process. Neither of these processes involves any change in the actual operation of drawing, but in the preparation of the wire for drawing, they differ widely.

In dry drawing, the wire is cleaned with acid, coated (usually with lime), baked, and drawn dry through a lubricant in the die box. The wire is first pointed by suitable means and then pulled through the die with tongs until sufficient wire is available to attach to the wire drawing block (Fig. 1). When this block revolves, it coils the wire about itself, continuously draws the wire through the die, and brings about the fixed decrease in sectional area.

In wet drawing, the wire, after acid cleaning, is immersed in a dilute solution of copper or tin sulphate, or a mixture of both, depending upon the color desired. The coils are then removed and placed in a vat of fermented liquor made from rye meal and yeast from which they are drawn wet, with the liquor serving as a lubricant.

Cleaning and Baking—The cleaning of hot rolled rods before the wire drawing is the basis for success or failure in the production of good wire. Roll scale, if left on the rods, will not only reduce the life of the wire drawing dies but will cause scratches and surface imperfections that never draw out. Overcleaning with pitting will produce rough surfaces. Muriatic acid is sometimes used, but a hot (185°F.)

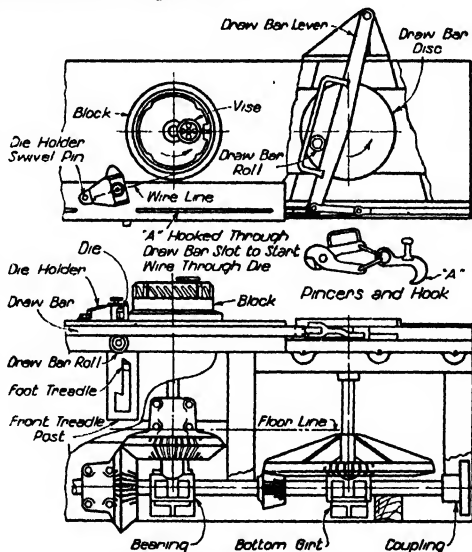


Fig. 1—Wire drawing block.

*District Director of Research, American Steel & Wire Co., Worcester, Mass.

solution of sulphuric acid is more commonly used for cleaning or "pickling." Acidity of the cleaning solution and time of immersion are regulated according to the analysis and the type of steel being cleaned. High carbon steels are cleaned in stronger acid solutions and for relatively shorter periods of time; low carbon steels, in the lower acidities, for longer periods of time. Low carbon basic steels require stronger acid than Bessemer steels. Inhibitors should be used to prevent excess waste of steel and acid; also to prevent pitting and excessive fuming.

Wire rods, after being cleaned in acid, are rinsed in cold water and washed with a high pressure hose. Usually they are then dipped into a vat of lime emulsion for coating, although they may be dipped in copper sulphate or be given a sull coating (a brownish wet rust produced by water spraying after acid cleaning) before the lime dip, if it is so desired. Lime emulsion is used either cold (120°F.), or hot (180°F.). Cold lime, when used, has a concentration of 3-5%. Hot lime is used in the following concentrations: light 3-5%, medium 6-9%, heavy 10-12%, extra heavy 12-15%. The larger the number of drafts, the heavier the lime coating. The limed rods are baked at a suitable temperature for a period of time sufficient to dry thoroughly and to remove acid brittleness.

Drawing—Dies—While chilled cast iron, cast chromium steel, and forged steel dies are still used, tungsten carbide dies are rapidly displacing them. Diamond dies are still preferred on very small sizes of 0.010 in. dia. and under, up to 0.025 in. dia. for finishing drafts. Because of limited production of "shape" wire, hardened punched chromium steel dies are employed.

Machines—Wire drawing is usually accomplished by means of an equipment known as a wire drawing frame. Each frame is composed of a bench with several wire drawing blocks. Fig. 1 shows one block of such a section, with the die box, die holder, and the draw-out mechanism for drawing the first few feet of wire through the die. Frames are usually referred to as "rod frames" and "wire frames," according to the use to which they are put.

Bull Blocks are used for very large sizes of wire up to $\frac{1}{2}$ in. dia. This equipment is a large single block, built for tremendous strength and power. On such equipment, rods are usually drawn one draft with $\frac{1}{2}$ - $\frac{3}{4}$ in. reduction.

Draw Benches are used for the large sizes of rounds and shapes which are later to be straightened and cut to length. See the article on Cold Finished Carbon Steel Bars and Shapes.

Double and triple deck wire drawing blocks are so arranged that two and three drafts may be drawn at the same time by a special arrangement of die holders with respect to the two or three elevations of blocks.

Continuous dry drawing machines are used for successively drawing several drafts by suitable equalizing of the successive speeds from one block to the other, or by arranging storage capacity on each succeeding block to make up for the net increase of wire at each stage.

Continuous machines for wet drawing fine wire are used from 4-13 successive drafts. They generally consist of cone-like wire drawing blocks, so designed that the steps of the "cone" accommodate the increase in the length of wire with a minimum of slippage. The lubricant is forced in a stream to the dies in some types, while in others the dies are immersed in the lubricant.

Lubricants—A large variety of drawing lubricants are used, depending on the number of drafts and the finish desired. The most common lubricants are:

Grease, used for one to three draft wire;

Soap, used for one to six draft wire;

Liquor, used for wet drawing, made from water and rye meal flour which is allowed to ferment. The metallic coating of copper, or copper and tin, requires no other lubricant than this liquor; but the percentage of reduction per draft must be less than in the case of dry drawing.

Reductions—The per cent reduction of area per draft is figured thus:

$$\% \text{ reduction of area} = \frac{100 (S-s)}{S}$$

Where S equals area of original section and s final section.

Low and medium carbon wires are reduced 40% and less per draft, whereas higher carbons are reduced only 30% and less per draft. Wet drawn wires are reduced only 18% and less per draft.

Process Heat Treatments—In order to obtain the desired properties for certain

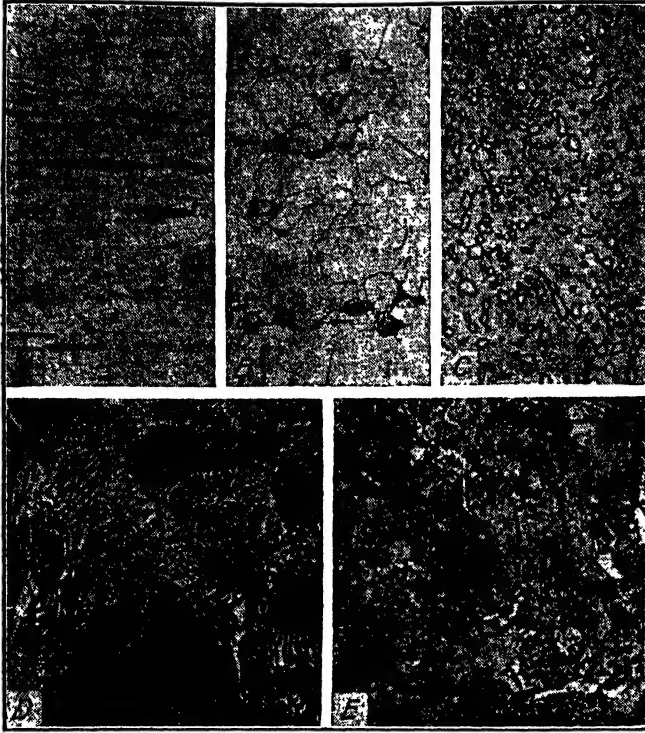


Fig. 2—"A" hard drawn structure before annealing, C 0.09%, X 250. "B" structure after annealing "A," X 250. "C" spheroidized structure, C 0.98%, X 1000. "D" structure after air patented, C 0.70 and mn. 0.73%, X 1000. "E" same steel as in "D" after lead patented, X 1000.

wires, the rods or process wire are given a heat treatment to develop the proper microstructure.

For low carbons, the most common heat treatment is annealing at temperatures in the vicinity of, or slightly lower than, the critical range.

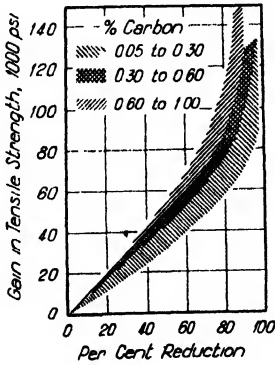


Fig. 3—Increase in tensile strength with increase in reduction.

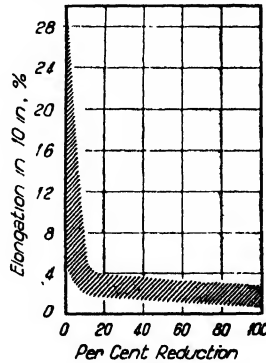


Fig. 4

Fig. 4—Effect of reduction on elongation. The carbon content varying from 0.05-1.00%

Process annealing recrystallizes the ferrite so that further drafting may proceed to finer sizes. Fig. 2A shows a hard-drawn structure before such an annealing. Fig. 2B shows a structure after annealing.

Medium and high carbon steels are sometimes spheroidized, when soft wire is

required, or when this structure is desired before a final heat treatment (Fig. 2C). Medium and high carbon steels are more frequently patented either in air or in lead to give a fine pearlitic structure, often referred to as "sorbite," in order to obtain a high initial strength and the best characteristics to permit drawing to high tensile strengths. (Fig. 2D, air patented, and Fig. 2E, lead patented.)

Finishes—Many of the finishes are the natural result of the coatings and lubricants used in the wire drawing practices. Others are the result of special coatings added to the wire after drawing. The more common finishes are designated as black, bright, black annealed, bright annealed, liquor finish, coppered, tinned, and galvanized.

Coils and Straightened and Cut Lengths—The following coil sizes are employed, with the approximate wire sizes:

Size	Dia. of Coil
0.027 in. and finer	8 in. coils or spools
0.028-0.073 in.	12 or 16 in. coils
0.074-0.375 in.	22 in. coils
0.375-0.687 in.	26 or 28 in. coils
Coarser than 0.687 in.	Straight and cut to length

If desired, all sizes may be straightened and cut to specified lengths, bundled and burlapped, or boxed.

Physical Properties—Regardless of the initial tensile strength of a low, medium, or high carbon steel in the green, annealed, or patented condition, the gain in tensile strength, owing to increased drafting, follows a reasonably definite trend as shown by Fig. 3. The elongation also follows a definite trend, and the losses are shown in Fig. 4. The physical properties of typical medium carbon steel are shown in Fig. 5 as the percentage of drafting increases.

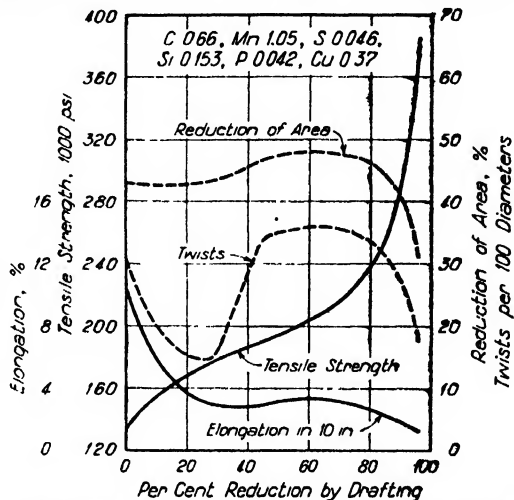


Fig. 5—Effect of reduction by cold drawing on the properties of carbon steel. Initial size of rod was 0.304 in. dia. The initial condition was OF Patented

Cold Finished Carbon Steel Bars and Shafting

By H. W. Graham*

Definition and Application—The cold finishing of steel, generally used for bars and shafting, may be defined as the process of reducing their cross sectional area, without any heating, by one of five methods:

1. Cold rolling; 2. Cold drawing; 3. Cold drawing and grinding; 4. Turning and polishing; and 5. Turning and grinding.

Cold finishing is employed principally for one or more of the following reasons: (a) Special size accuracy; (b) smooth or bright surface finish; (c) improved physical properties; and (d) better machinability.

The selection of the method to be used is governed either by economic reasons, section, or the necessity to meet requirements characteristic for one of the methods. For example, the usual practice is to cold draw the smaller sizes of rounds up to about 3½ in. and turn the larger sizes. Whenever a superior finish or size accuracy is required the material is ground. Turned and polished bars, usually over 1½ in., are furnished where hot rolled physical properties and cold finished size accuracy are desired plus a finish that is reasonably free from the normal surface imperfections of hot rolled bars.

Historical—Cold finishing first appeared in 1859, as a cold rolling process for wrought iron, invented and patented by Bernard Lauth. Later, the same process was used on steel, primarily for shafting for power transmission units, machinery, and agricultural implements.

Cold rolling, as a means of cold finishing, gradually lost ground after developments in the wire industry disclosed that drawing the larger wire sizes through dies produced practically the same improved physical properties. Finally, in about 1890, the two processes were considered interchangeable from the standpoint of effect, and although cold rolling was never replaced completely, and is still used for certain purposes, such as wide flats, the principal method of producing cold finished steel today is by cold drawing.

The growth of the cold finished industry during the past thirty years is largely attributed to the demands for the cold finished product that accompanied the rapid development of the automotive, electrical equipment, and machinery industries. The producers of cold finished steels have kept pace with the progress of these industries by providing a variation of standard and special analyses, finishes, and treatments in order to satisfy a diversified range of requirements.

Description of Cold Finishing Processes—General—Since the surface defects and imperfections present in the hot rolled product are accentuated by cold drawing, it is necessary that the preparation of the hot rolled material for this purpose be surrounded with precautions to assure the proper cold finished surface quality, size and finish. In fact, the surface requirements of hot rolled bars for cold finishing purposes are similar to those practiced for forging steel; that is, the surface must be substantially free from seams, pits, and excessive scale.

Prior to cold drawing, the hot rolled material is usually immersed in a bath of 4-8% sulphuric acid, at a temperature of about 150°F. until the scale is completely removed. It is then washed and dipped in a lime solution which neutralizes any acid that may be remaining on the bars, and also serves as a rust preventive and a lubricant in the finishing. Drawing through a die, straightening, and then cutting to length complete the sequence of operations.

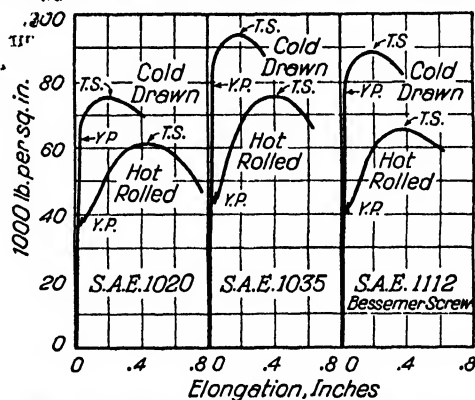


Fig. 1—Typical stress-strain diagrams of hot rolled and cold drawn steels.

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Cold Rolling—Cold finishing by cold rolling involves passing the hot rolled bars, cleaned of scale, repeatedly through a set of rolls, thereby subjecting the material to a light reduction in each pass, until the final size is obtained. Cold rolling imparts a bright surface finish, accurate size, and an appreciable increase in the tensile strength with an even greater increase in the yield point.

Cold Drawing—In this method, a hot rolled bar of practically any shape, after having been cleaned of scale, is pulled cold through a die whose bore section is generally $\frac{1}{16}$ - $\frac{1}{8}$ in. smaller than the hot rolled dimension or thickness. The amount of draft, however, may be varied from $\frac{1}{16}$ - $\frac{1}{4}$ in., depending upon the analysis of the material being drawn, the hot rolled size, and the physical properties desired. The effects of cold drawing are similar to cold rolling, the final product having a bright surface finish, accurate size with its tensile strength and, particularly the yield point, materially increased.

Cold Drawing and Grinding—For purposes where the size accuracy, surface finish, straightness or concentricity imparted by cold drawing, or turning and polishing are inadequate, grinding after cold drawing is resorted to. The physical properties of this type of cold finished product remain unchanged from those of the cold drawn bar.

Turning and Polishing—Whereas cold drawing reduces the cross sectional area by subjecting the bar to compressive and elongating forces, turning and polishing accomplishes the same by turning a $\frac{1}{16}$ - $\frac{1}{8}$ in. from the diameter, depending on the bar size, usually followed by polishing and straightening in a combination straightening and polishing machine. By this method, close size accuracy is obtained, similar in degree to that of cold drawing, but the finish of the surface is somewhat brighter, and surface decarburization, surface seams, and other minor hot rolled defects which are not affected by the cold drawing operation are removed. Since the steel has not been cold worked in any appreciable manner, the physical properties of the hot rolled bar follow through to the turned and polished product.

Turning and Grinding—In this process, after the hot rolled bar has its rough and imperfect surface removed by turning, it is ground, usually in the centerless type of machine, resulting in a product whose finish and characteristics are similar to cold drawn and ground material, except that the hot rolled physical properties have not been changed.

Size and Finish—From the above discussion, the various methods of cold finishing may be grouped as follows according to superiority of size and finish:

Size Accuracy	Finish
First—Turning and grinding or cold drawing and grinding.	Turning and grinding or cold drawing and grinding.
Second—Turning and polishing or cold drawing.	Turning and polishing.
Third—Cold rolling.	Cold drawing or cold rolling.

One of the outstanding advantages of cold finished steel is the close size tolerance that can be maintained. Cold finished bars are straightened commercially within $\frac{1}{32}$ of an in. in 5 ft. Rounds for shafting purposes are held considerably closer, and even better straightness requirements can be met by special processing in straightening.

Physical Properties—Table I gives average physical properties of cold drawing, hot rolled bars of the various analyses listed. The data presented are general in nature, and should therefore not be interpreted as values necessarily obtainable in all cases, sizes, and conditions. Also the stress strain diagrams in Fig. 1 give a general idea of the marked increase in tensile strength and particularly yield point that occurs in this process. The tensile strength is not raised as much as the yield point, but since permanent distortion is a function of the yield point rather than of the tensile strength, this effect upon cold drawn materials is of vital importance in applications in machinery.

The increase in yield point is accompanied by a decrease in elongation and reduction in area, but not enough to materially interfere with the use of such materials where the higher yield points are necessary. A cold drawn bar of properties intermediate between the extremes in yield point and elongation can be obtained by annealing or normalizing treatments.

Because of its desirable physical properties, cold drawn bar stock is often applied in substitution for heat treated bars, since it is not as costly, and is easier to machine. Also, in applications where it is desired to have heat treated properties

Table I
Average Physical Properties of Cold Drawn Steel
Sizes $\frac{1}{2}$ -2 in. Dia. Test Specimens 2 \times 0.505 in.

S.A.E. Steels	Tensile Strength	Yield Point	Elongation in 2 in., %	Red. of Area, %	Brinell Hardness No.
1010	67,000	55,000	25.0	57.0	137
1015	71,000	60,300	22.0	55.0	149
1020	75,000	63,700	20.0	52.0	156
1025	80,000	68,000	18.5	50.0	163
1030	87,000	73,900	17.5	48.0	179
1035	92,000	78,200	17.0	45.0	187
1040	97,000	82,400	16.0	40.0	197
1045	102,000	86,700	15.0	35.0	207
1112	87,000	73,900	17.0	45.0	183
1120	78,000	66,300	19.5	49.0	159
X1314	80,000	68,000	19.0	51.0	163
X1315	82,500	70,100	18.5	50.0	167
X1330	98,000	83,300	18.0	40.0	201
X1335	105,000	89,200	16.0	35.0	217
X1340	112,000	95,200	14.0	30.0	223

along with the more accurate size tolerances, hot rolled bars may be heat treated in accordance with the requirements and then turned and ground, or turned and polished.

Of late, some attention is being given to the effect of strain drawing cold drawn bars at temperatures in the neighborhood of 500 and 600°F. Such low temperature treatments have practically no deleterious effect on the close size or smooth finish of the cold drawn bar, and are instrumental in boosting the tensile strength and yield point without sacrificing ductility. This phenomenon is of value for further increasing the strength of cold drawn steel.

Machinability—Another important advantage of cold finished materials is its superior machinability as compared with a hot rolled product. This superiority depends upon several features including an improved machining quality in the steel itself if cold drawn, resulting from the effect of cold drawing and if cold finished under any of the standard methods better machining performance because of freedom from hot rolled scale, close size accuracy, and greater degree of straightness. These advantages are recognized generally by buyers interested in machining quality as indicated by the large percentage of cold finished steels used by machine shops, particularly automatic screw machine work where the machining requirements are most exacting and severe.

Inspection and Testing—To insure a cold finished product that will perform satisfactorily for the diversified application of its users, it is necessary for the steel producer to furnish a quality of the highest caliber. The standards of practices adopted for steel making, preparation and inspection of semifinished sections, and inspection of the final bar are the equivalent of those enforced for forging steels.

Precautions are taken during the making and rolling of the steel to minimize chemical irregularity, seams, pipe, and other defects, surface or internal. After cold finishing, the bars are inspected closely for these same defects, as well as inspected for size, straightness, out-of-round, appearance cutting, and suitable bundling, marking, and loading.

Shafting—It is believed appropriate to include in this discussion a brief mention of shafting formulas; more detailed discussions are published in bulletins of American Standards Association.

Shafts for transmission of power are subjected to transverse and torsional forces. The loads producing these forces are the torque resulting from the resistance offered by the power load to the revolving shaft; the belt pull, the weight of the pulleys, gears, sprockets, drums, and the weight of the shaft itself. In designing a shaft, it is therefore necessary that the stresses to which the shaft is subjected be within the safety limits of the material used.

For ordinary transmission of power through shafting, experience has shown that when velocity of rotation and spacing of shaft hangers are kept within defined

limits, the following formulas answer all practical requirements of design (the limitations of these formulas are that the shafts be supported at no greater intervals than 8 ft. and that the r.p.m. be no greater than 400).

D = diameter of shaft in inches.
N = number of revolutions per minute.
H = horsepower.

For head shafts.....	$H = \frac{D^3 \times N}{125}$
For line shafts.....	$H = \frac{D^3 \times N}{90}$
For short countershafts and single power transmitters.....	$H = \frac{D^3 \times N}{50}$

Conclusion—The uses of cold finished steels have become so widespread that their applications are too numerous to attempt to cover completely. The more common uses are for spark plug shells, radio speaker cores, bolts, nuts and screws, gears and pinions, typewriter, sewing machine and cash register parts, chain pins and rolls for silent chains, motor and transmission power shafting, motorcycle crank axles, oil pump shafts and gears, piston pins, steering gear arms, bushings, pins and worms, tie rods, wringer rolls, gun parts, and commutators. Industries such as manufacturers of automobiles, motorcycles, sewing machines, typewriters, adding and calculating machines, textile machinery, shoe machinery, railroad, agricultural implements and electric equipment are particularly large consumers.

Swaging

By W. L. Bowen, Jr.*

The term "swaging," as used here, refers only to rotary swaging (rotary reduction), and is not to be confused with coining or other types of press work.

Construction and Operation of Swaging Machines—The modern swaging machine is simply a mechanical means for rapidly opening and closing two dies (sometimes four dies). The dies are carried in a slot in the face of a revolving spindle and are held between a pair of steel blocks called backers. Outside of and around the spindle is a circular roll cage containing loosely a number of hardened steel rolls.

The revolution of the spindle causes the backers (and dies) to pass between successive pairs of opposing rolls, thus forcing the dies together. With a spindle r.p.m. of 500 and with 10 rolls, there would be, approximately, 3,000 die blows per min. Actually, this is reduced somewhat because the roll cage rotates slowly, thus lessening the number of blows.

The dies are blocks of hardened steel which have upon their inner faces the impression of the shape or the diameter of the work it is desired to produce, with one end of the die groove flared to allow the unreduced stock to enter, Fig. 1.

Uses of Swaging—Since the dies rotate around the work, it is obvious that the swaged portion must assume a round cross section, even though original work can be of any regular cross section such as square, or hexagonal.

The tapering of tubes (welded or seamless) or drawn steels can best be performed by swaging. Rods, bars and wire are also reduced or tapered economically by swaging. Gold plated wire, for instance, can be swaged with the plate kept intact and evenly distributed all the way to the end of the swaged section.

Speed of Swaging—Naturally the speed of swaging depends upon many factors, such as kind of material, angle of taper, amount of reduction, or finish desired. In general, the speed varies from 1 in. per sec. up to 4 in. or perhaps 5 in. per sec., making little difference whether the work is fed into the dies automatically or by hand, although automatic feeding is always slower than hand unless hydraulic equipment is used.

Physical Effect of Swaging—Swaging is actually performed more by pressure than by blows. Hence there is a flow and readjustment of the grains of the swaged metal.

Most metals tend to work harden when cold swaged so that annealing may often be necessary after one, two, or three swaging passes, depending upon amount of reduction and type of material. This is particularly true of stainless steels.

Some extremely brittle metals, such as a tungsten bar, when hot swaged in a series of passes, can be made ductile enough so that further reductions can be made by drawing.

Since the entire volume of the metal being swaged is not lessened to any appreciable extent, but rather is changed in shape, it follows that solid work, when swaged, tends to elongate. In the case of tubing, swaging tends to thicken the wall, since a volume equal to only 10% of the cross section goes into elongation.

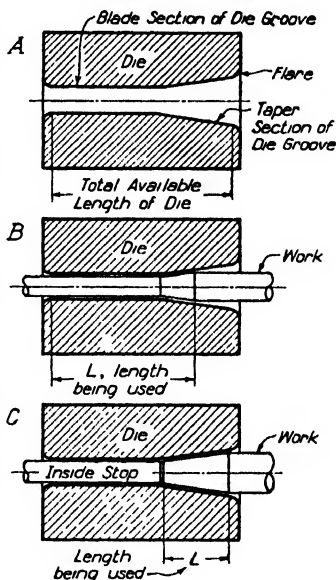


Fig. 1—Three views of the same die showing different values for "L." A shows the total available length, "L," of the die. B and C show two different jobs as swaged with the same die. In B the entire length of the blade section of the groove is used, plus approximately one-half of the taper section of the groove. In C only the length of the taper is being used.

*Sales Manager, Swaging Machine Dept., The Torrington Co., Torrington, Conn. Prepared for the Subcommittee on Forging. The membership of the subcommittee was as follows: Adam Steever, chairman; R. W. Thompson, F. B. Foley, O. W. Ellis, H. M. Spears, W. E. Jominy, W. W. Criley, and J. H. Friedman.

The thickening of the wall is simply due to the flowing metal following the line of least resistance.

Amount of Reduction—The amount of reduction in any one pass depends upon various factors such as type of material and angle of taper, but in general the maximum reduction in one swaging pass should not be over 30% of the cross sectional area.

Because the die pressure is in a radial direction around the work, it will be obvious that steep angles or abrupt tapers are to be avoided. For easy, commercial swaging the included angle of taper should not be over 10-12° or less, depending upon force available for feeding.

Swaging Machine Capacities—Various metals have differing ultimate compressive strengths and therefore require varying swaging pressures in order to obtain a reduction. For all practical purposes, flowing or swaging pressures may be considered to be 1.75 times the ultimate compressive stress of the material being cold swaged. (No figures are given for comparative pressures for hot swaging because of the large number of variable factors.)

It must be borne in mind that the figure for swaging pressures given above does not hold good when the length of swage within the swaging dies exceeds ten times the diameter of the work (this applies to solid work only), due to the restriction of endwise flow of the work resulting from surface friction between the dies and the work, which creates pressures in excess of the strength of the dies.

To obtain the maximum capacity of any given swaging machine the following equation may be used:

$$\frac{T}{S \times 1.75 \times L} = D$$

Where D = the dia. of the work, in inches
 L = the length of the die being used, in inches (See Fig. 1)
 S = the ult. compressive stress of the work in psi.
 T = the total capacity of the machine in lb.

The figure for "S" can be obtained from any materials handbook and the value for "T" from the swaging machine manufacturer. Obviously the value for "L" depends upon the job, so may have a different value for each job.

Example—A manufacturer has some material of a certain dia. to be swaged and wants to know if it can be handled without overloading his swager. The swaging machine has a total capacity of 400,000 lb. with a die length of 3 in., all of which length is to be used (Fig. 1).

The material to be swaged has an ultimate compressive stress of 150,000 lb. so the example is solved as follows:

$$\frac{400,000}{150,000 \times 1.75 \times 3} = 0.507 \text{ in. dia.}$$

Thus 0.507 in. dia. work could be safely swaged in this instance.

From the above equation, it is obvious that as "S" is reduced "D" is increased and vice versa, so the allowable projected area in the swaging die grooves (the length of taper \times average dia. of taper) varies inversely as the compressive strength of the material being swaged.

Similarly when only a part of the available length of the swaging die is used, larger dia. work can be safely handled (Fig. 1C).

The limiting factor for "D," of course, is the actual width of the dies. For instance, if it was required to determine the maximum dia. of zinc or a similar material that could be swaged on a certain machine, the value for "S," 70,000, might be so low as to cause the value for "D" (dia. of the work) to be greater than the width of the swaging dies.

Coining

By Guy R. Houghtaling*

Introduction—Coining is a method of cold forming or sizing, by compression, an article made of gold, silver, copper, zinc, tin, nickel or other metals. In recent years, iron and steel parts have been subjected to cold sizing for the purpose of imparting smooth finishes and close tolerances and in numerous instances this coining operation is more economical than producing this finish by cutting tools. A gasoline engine connecting rod is an example where coining is used extensively to size the bosses at crankshaft and wrist pin ends, to within limits of plus or minus 0.001 in. The dies used are generally plain, hardened blocks, having stepped parallel surfaces between which the steel forging (which is about $\frac{1}{2}$ in. larger) is squeezed to size.

Nothing definite can be stated about the percentage of reduction by coining, as each individual job has its limits, which are usually governed by the ability of the steel (in the dies) to withstand constant pressure. A good rule is to use 25% of the ultimate compression strength of the dies in question, for work which is confined. On work which is not confined 50% of the ultimate compression strength of the die steel can be used on production runs.

Methods of Coining—*Drop hammers* can be used when the pressure is not extreme and where the material will flow readily into the dies. Drop hammers exert instantaneous pressure on the article being struck.

Coin presses are usually associated with powerful presses whose slide movement is actuated by a knuckle joint between the slides which is operated by an eccentric or crankshaft.

Screw presses (percussion) utilize a multiple thread screw to which is attached a heavy fly wheel which stores energy and, on a fast downward movement, exerts a powerful pressure on coin dies.

Hydraulic presses are fast becoming adapted to coining work. The modern one unit press can be made to operate fast and with high pressures. These presses can be so regulated that only a definite pressure can be exerted upon the dies. One distinct advantage is that the action of the hydraulic press permits the metal to take a more definite set due to the length of time in compressive action.

Annealed mild steel, with about 0.20% carbon, requires about 50 tons psi. to start plastic flow. This increases as the article becomes harder and the operation must be stopped before reaching the compressive strength of the coining die steel.

Hydraulic presses permit using the greatest amount of the operating time cycle in actual squeezing, having a fast closing of the dies and a fast opening. This sometimes runs to $\frac{3}{4}$ of the time cycle in squeezing, and $\frac{1}{4}$ each to close and open the dies.

Coining Die Steel—The steel for the coining dies is largely a matter of personal preference. Carbon steel, formerly used, is usually shallow hardening and although it becomes very hard on the surface it will not withstand intense pressures. Tool steel manufacturers supply a chromium-nickel-molybdenum drop forge die block steel having about 0.65-0.70% carbon which is pack hardened and oil quenched. This steel has a high compressive strength, holds its shape well during heat treatment and upon proper tempering gives a coining die of long life. Many other steels are suitable, and where simple finishing by machining and grinding can be done, the high carbon high chromium steel is excellent. Modern high production schedules require coining dies to withstand tremendous pressures repeatedly and only steel having the ability to be heat treated for deep hardness fills the above requirements.

Coining Dies are usually made by sinking a hardened hub into a soft die block. This hub is a faithful reproduction of the article to be coined, and from its impression in the die block comes the article to be manufactured. Most of the details in the actual making of coining dies are arrived at by long experience, careful observations, and the most careful and painstaking heat treatments. Metals will work harden when squeezed between coining dies, so to get economical production from the dies, it is important to control this condition by annealing.

Because of the large amount of flow required on numerous articles being coined (for example, men's finger rings), the metal will work harden before it is possible

*Hickok Mfg. Co., Rochester, N. Y. Prepared for the Subcommittee on Forging. The membership of the subcommittee was as follows: Adam Steever, chairman, R. W. Thompson, F. B. Foley, O. W. Ellis, H. M. Spears, W. E. Jominy, W. W. Criley, and J. H. Friedman.

to fill the die completely. It is then necessary to anneal the blank and sometimes to restrike a number of times with an anneal between each strike. As the work hardened metal requires such enormous pressure to make it flow, the coining dies do not have sufficient compression strength to resist sinking, so it is most important to anneal the blanks whenever necessary.

It is very important to have clean blanks at the start of the coining operation and perfectly clean blanks after annealing and before restriking. Most copper base alloys require a red heat to anneal and unless a protective atmosphere is used during heating, the parts will have to be pickled and washed. Coining dies must be kept clean. This can be done with degreasing solvents and frequent use of bristle brushes. Small particles are bound to be removed from blanks during coining and a die can easily be split because of this condition. Another important precaution is to keep the smallest drop of moisture (water or oil) from getting into deep cavities. Metal will not flow into cavities containing moisture.

Various Methods of Coining—Usually, money is coined in a hardened ring, inside of which are the upper and lower dies. Just enough metal is used in the blank to size the coin accurately. Spectacle frames are made from "found blanks" (blanks with just enough metal and proper dimensional sizes to fill the dies). Spectacle parts and jewelry items made of gold filled metal must come from the coining dies with the surface gold unbroken.

Numerous jewelry items are made purposely with a surplus of metal, which surplus is called flash-selva. These dies are economical to make where it is not necessary to hold thickness to exact dimensions. Therefore, any surplus not needed to fill either upper or lower dies is flowed over the edges of both upper and lower dies. This surplus or flash must be carefully controlled. Generally, a good rule is to limit the width of flash to not more than three times its thickness. Where it must be more, flash gutters can be cut in one-half of the die, next to the die line.

Roll Threading and Knurling

By L. A. Ward*

Roll threading is the process of producing a thread by impressing helical grooves in a metal object by means of suitable rollers or dies. Likewise in knurling, a design is impressed in a solid or hollow metal article by means of a roller or rollers which are forced against the work while it is being rotated, the rollers being embossed with the desired design. When considering mass production of bolts, screws, screw caps, and the host of other threaded articles now being produced, the economic advantages of roll threading at once become apparent.

In the case of solid articles such as screws, there is a saving of metal as well as a speeding up of production. A third advantage in the case of bolts and screws is the increased strength obtained by this method due to the cold working of the metal during threading. In the case of hollow articles, the advantages of roll threading are even more apparent, for if it were not for this method of threading the cost of such articles as threaded caps for bottles, flashlights, or electric light bulbs, would be prohibitive due to the necessity for increased wall thicknesses and the added cost of cut threads.

Although there is little published on the history of roll threading and knurling, we do find that as early as 1888 socket shells were roll threaded by the Edison Lamp Works and they had set up standard specifications for this work. Undoubtedly there was considerable of both this type of work and knurling much earlier, but little is recorded.

Knurling—Knurling is commonly done in three different types of equipment, which are: (a) Lathes; (b) automatic screw machines; and (c) special machines. It is felt that a description of the method can best be given by covering these three cases separately.

Lathe—The knurling done in lathes is commonly done on small runs of work, or in combination with spinning operations. It can be done by a hand tool such as is commonly used by a spinner or by a tool which is clamped in the regular tool post and moved against the work in the usual method. The roller for knurling in a lathe, especially when done by hand, is of any convenient diameter (usually about 2 in.). This is made of hardened steel with a design embossed on the circumference and in use this is pressed against the article to be knurled with sufficient pressure to give the desired depth of design.

Automatic Screw Machine—In automatic screw machines the knurling tool can be mounted either on the turret or on one of the cross feed attachments, or as a swing tool. In this article it is not felt necessary to give a detailed description of the tools and cam layouts necessary, as these are adequately covered in instruction books for the various types of machines. The speed used in knurling on brass rod in an automatic screw machine is usually the maximum spindle speed available, although for coarse knurls a slower speed must sometimes be used. The feed for the types of tools shown above is as follows:

Turret:	Feed 0.020 in.
	Return 0.040 in.
Side or swing:	Feed 0.004 in.
	Return 0.008 in.
Top:	Feed 0.005 in.
	Return 0.008 in.

Special Machines—For large volume production, it is frequently more economical to perform the knurling operation in a separate machine. There are a number of machines which are especially designed for this type of operation on either solid or hollow parts.

In these special machines the design of the arbor and pattern rolls is of extreme importance. This is also true for the automatic screw machine and, to a lesser degree, for lathe work. In the case of lathe knurling, the operator can watch the operation and see that the pattern matches as the work revolves, but in an automatic machine this is impossible and if the size of the roller, with relation to the work, is not correct the design will be neither uniform nor properly impressed if the work revolves more than once during the operation.

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For hollow parts the arbor and roller are geared together so that they mate properly. The arbor over which the article is placed has the male impression of the design embossed on it, and the size of this arbor is as large as will permit placing the article over the arbor and removing it. The design embossed on the roller is a female impression of the design to be placed on the object. In such machines the work is quite frequently fed into the machine through some automatic feeding device and the entire operation done automatically. Here again there is no need of going into the details of such feeding and knurling mechanisms, and for exact details consulting the manufacturers of these machines is suggested.

Roll Threading—Roll threading may be carried out in three different types of equipment, which are the same as for knurling; namely, (a) in lathes; (b) in automatics; and (c) in special machines. Roll threading is seldom done in ordinary lathes and then only in the case of special threads where it would be either impractical or uneconomical to set up a special machine. Such a case would be where it was desired to put a roll thread on an article which was much longer than would normally be handled.

Lathe—In this case, if it is a rod, a roll is fastened in a suitable fixture on the tool post set at an angle corresponding to the pitch, and the feed is set accordingly. A back rest would normally be used to support the rod, and it is frequently necessary to go over the thread a number of times in order to produce the desired depth.

Automatic Screw Machine—Considerable roll threading is done in automatic screw machines and the tools used are generally similar to knurling tools except that, instead of a design on the roller, a thread is cut on it in the opposite direction to that to be produced on the rod. For instance, if it is desired to produce a right hand thread on the work, the roller will have a left hand thread.

The diameter of the blank to be threaded is approximately the pitch diameter of the final thread. The outside diameter of the threading roll should be larger than the work, and is calculated from the following formula which is taken from the Brown & Sharpe Automatic Screw Machine Operators' Handbook.

$$\text{O.D.} = \text{Pitch Dia. of} \left\{ \begin{array}{l} \text{piece} \\ \text{to be} \\ \text{rolled} \end{array} \right\} \text{ minus } \left\{ \begin{array}{l} \frac{1}{2} \text{ single} \\ \text{depth of} \\ \text{thread} \end{array} \right\} \text{ times } \left\{ \begin{array}{l} \text{multiple} \\ \text{used.} \end{array} \right.$$

It is impossible to give any fixed multiple which will be suitable for all work, but the threading roll should be made as large as possible. Feeds and speed will be approximately the same as for knurling.

Special Machines—There are a number of special machines used for roll threading a great variety of work; for instance, there are special machines for roll threading of bolts and screws as well as those designed for the roll threading of caps and tubular objects. In the special machines for roll threading bolts and screws, the operation is carried out by using two suitable dies having impressions of the thread on their faces. One of these is stationary and the other moves in a plane parallel to the axis of the work and in a direction normal thereto. The dies for this are made of hardened steel and the thread is projected onto these. The blank used is approximately the pitch diameter of the bolt or screw being made. This method of producing a thread on a bolt is one of the most commonly used methods, and its greatest advantage is in the economy of the method and the increased production which is possible. The speed usually varies inversely with the size of the bolt or screw being threaded, but is usually in the range of 30-100 pieces per min.

In roll threading of sheet metal caps and tubular products, the design of thread has never been standardized to the same extent as that for bolts and screws, and there are a number of different systems of threads used. Apparently the only one which is really standard is the one used in the manufacture of electric light bulb socket shells and similar articles. This is the Uno system. Due to this condition, it is quite difficult to give exact information as to the relation of the size of shell to the outside diameter or pitch diameter of the threaded part. Also there is considerably more variation in this respect due to alloy and temper than there is with solid objects. This is due to the wide difference in physical properties from one alloy to another and from one temper to another in any one alloy.

In general, the shell diameter will be slightly larger than the pitch diameter. The arbor size is close to that of the blank so that it is just possible to fit the shell onto the arbor. The roller size is found by subtracting the single depth of thread

from the pitch diameter and multiplying by a factor similar to the method of calculating a roller size for use in the automatic screw machine. We find on special machines for roll threading of shells that multiples as high as 12 are sometimes used, but more commonly the multiple is approximately 4. The arbor and roller are mated through gears as for knurling. The roller, depending on the multiple used, will have a single, double, triple, or quadruple thread. For instance, when the multiple used is 2, there will be a double thread cut on the roller. In use, the shell is usually fed into such a machine automatically and the operation carried out and the threaded shell discharged automatically. Speeds on such machines vary so greatly that it is impossible to give any definite limits.

Although no definite formulae for blank diameters are given for the various types of rolled threads, still the importance of finding and maintaining the correct one is extremely important and frequently the success or failure of roll threading a given article hinges on how accurately this size is maintained. In general too small a blank produces a poorly developed thread which is usually under size, while too large a blank usually produces an over size thread which is frequently rough.

Machinability of Steel*

Part 1—Introduction—In the machining of metals, the metal being cut, the cutting tool, the cutting fluid, the process and type of machine tool, and the cutting conditions all influence the results. By changing any one of these factors, different results will be obtained. It appears impossible to have a set of cutting conditions which will satisfy all phases equally. It is imperative, therefore, to adjust a combination of factors for the most effective compromise.

Definition—Machinability is a term used to indicate the relative ease or satisfaction with which a material is machined by sharp cutting tools in operations such as turning, drilling, milling, broaching, threading, reaming, sawing, or grinding. It is evaluated in several different ways depending upon the objective. These objectives vary widely in commercial machining and may refer to tool performance as represented by the tool life per grind under given conditions; the speed at which the material may be cut under different conditions for a given tool life; the force, energy or power required in cutting; the surface finish produced; or the dimensional accuracy maintained under given conditions between like pieces.

Values of machinability usually are comparative and represent the behavior of the material under given conditions. The tool material, shape, and size; the size and shape of the cut; the cutting fluid used; and the cutting speed must be held constant in order that the values may be directly comparative. If any one of these variables is changed for the tests, other directly comparative results will be obtained which may be out of agreement with those of the first test. Also, the machinability rating of a material as determined by one process may be different from that obtained by another process.

Materials Cut—Many materials have best or optimum cutting conditions, such as speed, feed, depth, tool shape, tool material, or cutting fluid; some or all of which are different from others, so that machinability ratings for these materials for practical purposes should be determined under these optimum conditions. The values of machinability for different materials then will be comparative, although the details of the tests are individual.

Tests for Machinability—The factors of importance in machinability are cutting speed, tool life, power consumption or cutting force, the finish left on the cut surface, and the accuracy of dimensions of the finished product.

Many types of tests have been developed for indicating the machinability of a given metal. If machinability is to apply to the tool, then the material cut should be constant; if machinability is to apply to the material, then the tool should be constant. Cutting fluids may be introduced as the variable, while the material and tool are held constant. Machinability may be expressed as:

1. The life of the cutting tool in turning, milling, drilling, broaching, tapping, or sawing, when cutting under fixed conditions of speed, feed, depth of cut, and with a given cutting fluid.
2. The force, energy, or power required when cutting by various processes, such as milling, turning, drilling, or the energy required to remove a single chip of a given size or shape in milling.
3. The torque and thrust in drilling or counterboring.
4. The suitability as measured by
 - a. The rate of penetration of a drill in a given time under a constant feeding pressure;
 - b. The traverse of a turning tool when fed against the work by a constant pressure as in the case of cutting off; and
 - c. The time in minutes or number of strokes to cut off a given cross sectional area with a hacksaw subjected to a given feeding load rather than a positive rate of feed.
5. The condition of the machined surface produced by the cutting tool on the material being cut.
6. The cost of removal of 1 cu.in. of the metal under specific conditions. This would involve both power and tool cost.
7. The temperature developed at the tool point.

Factors Affecting Machinability—A summary of the factors affecting machinability in accordance with the above definitions are as follows:

1. Material being cut, its analysis, structure, shape, and size.

*Prepared for the Subcommittee on Machinability of Steel by O. W. Boston, University of Michigan.

The membership of the subcommittee was as follows: O. W. Boston, Chairman; A. L. Boegehold, and H. J. French.

2. The cutting speed, size, and shape of cut.
3. The cutting tool, its material, quality, treatment, shape, size, and condition.
4. The condition of the machine tools on which the cutting is done, together with the processes involved.
5. The cutting process. A given material may have different machinability ratings for the different processes as turning, drilling, milling, and grinding.
6. Factors involving rigidity of the tool and work-holding device.
7. The characteristics of the cutting fluid used.

The optimum or best cutting condition involves the material being cut, the tool, the mechanical device, and the cutting fluid. For any material being machined, there is obviously a certain specific combination of conditions which is best. In order to secure the greatest production at the least cost, the cutting tool should be of a given material of a certain definite quality. It should have a certain contour of cutting edge, and combination of angles influencing its geometrical shape. A certain cutting fluid having properties peculiar for the given conditions should be used, and the mechanical equipment for the particular process involved should be suitable. If the physical properties of the material are changed, or if another material is substituted, some of the factors involving the tool, cutting fluid, or mechanical equipment also should be changed to maintain optimum conditions. The present state of the art of metal cutting leaves the selection of the various factors for a given problem to be determined largely by cut and try methods.

The steel cut, the cutting tool, and the cutting fluid used in any cutting operation present variables which affect machinability. Each is discussed separately below.

Part 2—Fundamental Principles—There are several factors involved in the machinability of steel which are closely associated with both the tool and the work, as discussed separately below.

Chip Formation—Chips of ductile metals are removed invariably by plastic flow. They are of two general forms: The ribbon or elementary type, and the sectional type. The elementary type, Fig. 1, is continuous and practically of uniform cross sectional area but made up of very thin transverse slip bands or elements. In the sectional type, Fig. 10, the small elements are grouped into clusters or sections of approximately equal size. Frequently these sections cling together to form a long, continuous chip, the outer surface of which is saw-toothed, but often the various sections become detached, giving broken up chips which are more easily disposed of.

Almost immediately after starting a cut, a small particle of the material being cut is trapped on the face of the tool and forms what is known as a built-up edge. The built-up edge is somewhat triangular in shape, being thickest directly ahead of the cutting edge, becoming thinner as it extends backward over the face of the tool, as shown in Fig. 1. This built-up edge occurs in all types of metal cutting, such as turning, shaping, drilling, sawing or milling. It protects the cutting edge of the tool by causing the undeformed material immediately ahead of the tool point to flow plastically into a chip which slides over the built-up edge on over the face of the tool.

The built-up edge is a function of the analysis and structure of the material being cut, the rake of the tool, the cutting speed, the cutting fluid, and the size of the cut. The thinner the chip, the smaller the built-up edge becomes and the more nearly the cutting edge of the tool cuts the material to leave a smooth finished

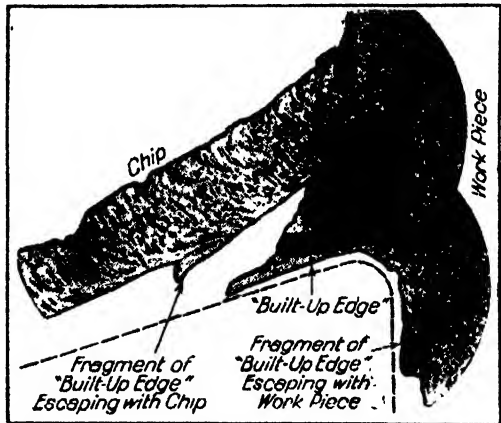


Fig. 1—Chip formation with a typical built-up edge on the nose of a lathe tool, turning steel. The bar was stopped suddenly after cutting for some time and the section at right angles to the cutting edge prepared. (Courtesy Hans Ernst).

surface. This surface is smooth, but appears as a torn surface similar to the face of a very fine-cut file. For thick chips, the cutting edge of the tool suffers only a small portion of the total work done, as it is protected by the built-up edge. The built-up edge appears to be a rather permanent structure as long as the cut is continuous. Portions of it may slough off and be carried away on the underside of the chip, and frequently portions of it adhere to the surface of the work as it passes the flank of the tool. See Fig. 1.

At low speeds, the built-up edge for a given condition is largest. As the speed is increased, it is reduced in size, particularly in height. At extremely high speeds, the built-up edge is smallest. When cutting at very high speed, as with cemented carbide tools, the built-up edge disappears and the cutting edge of the tool actually cuts and forms the machined surface which has the highest degree of surface quality.

Chatter—Frequently in the formation of the chips, because of the sliding of the elements into sections or because of the periodic sloughing off of the built-up edge, high-frequency vibrations occur. These vibrations may set up a natural period of vibration of the tool, of the work, or even of the whole machine, which may become very objectionable because of noise, poor surface finish, and possible damage to the machine. Rigidity of tooling, change in speed, feed, or depth of cut, or tool shape may cause the vibration to cease. Whenever long, thin chips are taken, such as with a large nose-radius tool or with a long, straight cutting edge, the danger of vibration is increased.

Surface Finish—The finish on the cut surface is improved as the built-up edge is reduced in size. This reduction may be accomplished by increasing the rake of the tool, using high speeds, reducing the size of the chip, changing the structure of the metal being cut, or introducing a cutting fluid, any one, or a combination of which is commonly used to secure better finish.

Surface finish in itself is a matter of great importance in machining operations of the finishing type.

Surface finish is not only important in connection with surface machining with single-point tools, but with surfaces made by abrasives and other means. The American Standards Association has a Committee on Surface Quality which has been working on this subject for the past six years. The first report was made to industry in Dec. 1938.

Surface qualities, by definition, are the physical characteristics of a boundary which separate solid substances. These qualities include such factors as the geometry of the surface in three dimensions, crystal structure, appearance, color, resistance to corrosion, hardness, size and shape of surface flaws. The committee report deals particularly with the geometry of the surface deviations from the nominal surface (cylinder, flat, sphere). These deviations are of three kinds: Surface flaws, waviness, and roughness, all three of which can be specified in inches. Surface flaws are occasional irregularities; waviness consists of widely spaced irregularities (more than $\frac{1}{16}$ in.), such as feed marks; and roughness consists of finely spaced irregularities (less than $\frac{1}{16}$ in.), which determine what is usually called "finish" of the piece. Flaws and waviness are now measurable, but roughness, being inside the waves, calls for a new measuring technique. The Committee has been concerned with the means of specifying roughness and has adopted the average height of the finely spaced irregularities as a measure of roughness. This height is expressed directly in microinches (millionths of an in.) across the surface in a direction to give the largest reading. It is recognized that this average height of irregularity is by no means a complete specification of any surface and that other information as to the character of the irregularities, as well as waviness, flaws, and other surface qualities, often will be required on practical problems. Consideration is being given to means of specifying some of these other surface qualities. A preferred set of roughness classes has been suggested by the Committee with appropriate symbols which range from $\frac{1}{4}$ microinch to 63,000 microinches, root-mean-square average.

During the past ten years a number of investigators have worked on equipment for measuring surfaces. The most widely used appear to be of three types:

1. Profile recorders which draw an enlarged graph of the actual surface profile. These are laboratory instruments. Two types have been described: (a) The Profilograph which uses mirrors, lenses, and a light beam.^{1, 10} (b) Electric profile recorder using vacuum tubes and cathode ray oscillograph.¹
2. Several arrangements of microscopic observations (profile microscope) with special illumination have been used to enable surface profiles to be observed directly.^{1, 11}

3. A Profilometer is a portable meter which does not draw a record of the profile, but which takes an automatic running average of the height of the surface irregularities and indicates this average directly on a meter. This instrument is portable, self contained, and has found direct application in the shop.¹

Tool Wear—When cutting steel with tools of carbon tool steel, tool failure is usually caused by wear on the flank of the tool directly beneath the active cutting edge. When cutting steel with tools of high speed steel, normal tool failure is caused by a gradual cupping of the tool on its face. After the chip is formed, it slides over the built-up edge protecting the cutting edge, and rubs against the face of the tool some distance back from the cutting edge, as shown at A in Fig. 2. The area of sliding contact between the chip and tool becomes heated, loses its hardness, and is abraded by the flowing chip. A groove is gradually worn into the face of the tool. It becomes larger and larger until its edge meets or nearly meets the cutting edge, as shown at B, Fig. 2. The flank below the cutting edge also may wear, causing the newly formed cutting edge to move toward the enlarging groove, as shown at C, Fig. 2. The built-up edge is gradually reduced in size from the start of the cut until the time the edge of the groove meets the cutting edge. A new irregular cutting edge is formed, resembling a ridge of mountains. The built-up edge at this point apparently disappears. The tool cuts most efficiently under this condition, but unfortunately the irregular mountain-like peaks break off and the tool quickly fails.

The progress of tool wear can be estimated readily from the color, shape, and size of the chip produced. In turning steel, the chips produced are first long and straight or only slightly coiled and are blue or purple in color at proper cutting speed. The color indicates the development of excessive heat even though the tool is newly ground and has cut but a small part of its total life. As the groove in the face of the tool is formed, the chips become coiled either in short spiral or long helical forms of small diameter. In this condition, the chip is at a lower temperature (no longer colored), and the tool cuts for the greater part of its life. As the newly formed cutting edge starts to fail, the chips become irregular in shape, rough on the bottom, and again blue in color.

This manner of wear and failure seems to maintain when taking both heavy and light cuts. The time of complete tool failure is easily observed when taking heavy cuts because of the sudden change in shape of the chips, the high blue color, and the burnished surface of the cut shoulder. When taking light cuts, however, the failure is similar but it is more difficult to determine the instant of tool failure. H. J. French and T. G. Digges⁴ used a trailer tool which was set to cut when the leading tool was worn so the test log became 0.002 in. larger in diameter. It has been found that there is practically no change in diameter of the work because of wear on the tool while taking a light cut until tool failure occurs, so that the trailer tool or any device which will indicate the sudden appreciable increase in work diameter does give a true value of the time of tool failure under light cuts.

Cutting-Speed Tool-Life Relation—For a given steel, tool, and cutting condition the life of a turning tool varies inversely with the cutting speed as indicated by the equation $VT^n = C$, in which V is the surface cutting speed in f.p.m.; T is the tool life under cut up to the time of tool breakdown measured in minutes; n is the exponent of T and equals the tangent of the angle of slope of the cutting-speed tool-life curve when plotted on log-log paper; and C is a constant depending upon the various conditions, such as type of material, size, shape, and material of tool, size

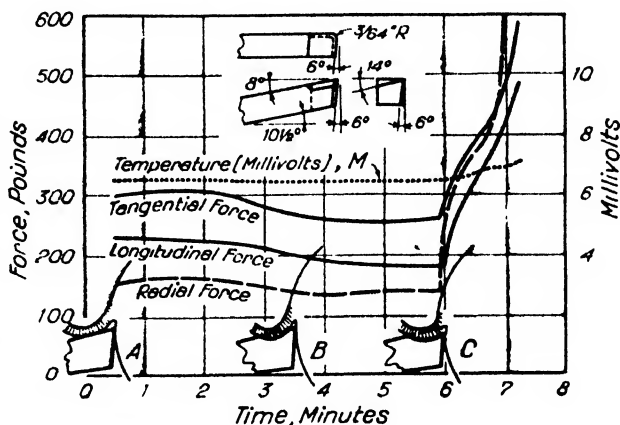


Fig. 2—Tool failure by a gradual cupping.

and shape of cut, and cutting fluid. This relation gives a parabolic curve on cartesian or rectangular coordinates, but a straight line on double logarithmic paper, as shown in Fig. 3.

It is shown in Parts 3, 4, and 5 that the constant C and exponent n will vary for practically every set of conditions as the steel, tool, or cutting fluid is changed, so that no single value of n in the equation $VT^n = C$ can be used safely to represent conditions in general.

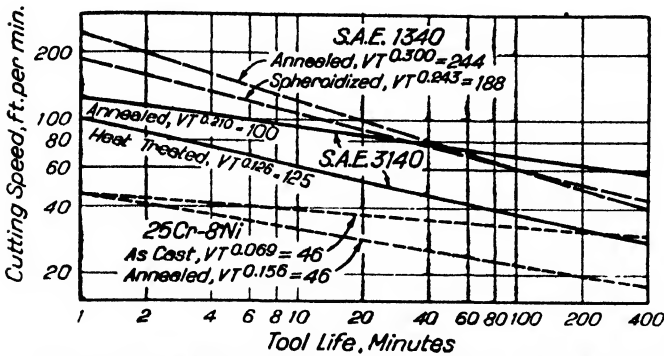


Fig. 3—Cutting-speed tool-life curves for various types and conditions of steel plotted on log-log scale. It is shown that each material with different structures gives a different slope to the curve, and that one equation is not suitable for all materials (see text).

determined by a thermocouple at all times during its tool life are shown when cutting dry an annealed S.A.E. 2335 steel at 145 f.p.m. The depth of cut was 0.100 in. and the feed was 0.0125 in. A high speed steel lathe tool was used which had an 8° back rake, 14° side rake, 6° end clearance, 6° side clearance, 6° end cutting, 0° side cutting-edge angle, and $\frac{1}{8}$ in. nose radius. The condition of the tool and the built-up edge at $\frac{1}{4}$, $3\frac{1}{4}$, and 6 min. after beginning the cut are shown in Fig. 2 at A, B, and C, respectively.

Part 3—Steel Cut—The steel cut presents many factors as outlined below, which affect its machinability:

1. Composition, such as carbon, alloy, or special steels developed for free machining which contain sulphur, lead, selenium, of manganese; 2. Melting and casting practice and grain size characteristics; 3. Fabrication: Cast, forged, drawn, or rolled (hot or cold finished); 4. Heat treatment; 5. Physical properties: Tensile strength, hardness, and work hardening capacity; 6. Metallographic structure; and 7. Size of material cut.

Composition, Heat Treatment, and Grain Size (Also see Section on Heat Treatment)—The machinability of steel varies with its composition, treatment, and structure. In cold finished bar stock for screw machine work, the lamellar pearlitic structure is best for the low and medium carbon steels. In the high carbon steel, such as S.A.E. 1095, a spheroidized condition increases tool life. It is reported that the best machinability of normal cold drawn steels is obtained with an elongation of 13-16% in 2 in. and a minimum reduction of area of 40%. There is a danger of reduced tool life if the elongation is below 10% and the reduction of area below 35%. In screw stock steels, well broken up chips, a good finish, and a long tool life at high speed are desirable but not always obtainable together. Alloy steels which work harden appreciably are machined in the hot rolled and annealed condition.

For favorable machinability, a normalizing treatment (or annealing) is recommended by H. W. McQuaid⁶ for the higher alloyed steels. In the case of carbon, carburizing steels, it is seldom necessary to normalize, as satisfactory machinability is usually obtained in the hot worked condition. In the fine grain, shallow hardening type of low alloyed steels, higher normalizing temperatures are necessary to obtain the lamellar pearlitic structure which has the best machining characteristics.

For rough lathe work where surface finish is of minor importance, low hardness is more important than low ductility. For finishing cuts on such steels as S.A.E. 6140, 4140, and 3140, tool life is impaired if the Brinell hardness is over 207, even though the structure is lamellar pearlite.

Steels of fine grain size (A.S.T.M. 5-8), when used as oil hardening or car-

Forces, Energy, Power Relation—Formulas for cutting forces in turning and torque and thrust in drilling are shown in Part 3; tools, Part 4; and cutting fluids, Part 5. It is shown that the values of the constant and exponents may vary as the material or tool shape is changed.

Influence of Tool Wear on Cutting Force—The three components of the cutting force and the temperature indicated in millivolts as

burized steels, are highly ductile, particularly if they are abnormal. They show less warpage in heat treatment and appear to be best for producing a fine finish. W. G. Hildorf states that: "In general, coarse grain size (A.S.T.M. 1-5) is better for heavy cuts. Steel of each grain size should be cut with tools appropriately ground. The resulting cost of metal cutting for each steel with favorably ground tools is approximately the same over a long period of time. Difficulty will be encountered, however, should an attempt be made to machine the coarse grain steels on a machine properly set up for machining fine grain steels."

For further discussion of grain size of steel, refer to the articles by R. L. Wilson.^{4, 12}

Cutting Speeds and Feeds in Turning—When steels are machined in turret lathes with tools of high speed steel properly ground for roughing cuts from $\frac{1}{4}$ - $\frac{1}{2}$ in. in depth and feeds from 0.020-0.060 in., the cutting speeds that give satisfactory commercial values of tool life, as recommended by Warner and Swasey Co., are as follows:

Steel	Surface ft. per min.
Alloy, annealed.....	50- 60
treated	25- 40
Castings, miscellaneous.....	50- 60
Machine, hard.....	35- 60
medium hard.....	60- 85
soft	100-120
Threading	25- 40
Tool, annealed.....	60- 80
unannealed	25- 35

Frequently the tools have to be ground to produce a certain shape of work which calls for reduced cutting speeds. At best the speeds recommended above are for setting up work and may be modified as experience and conditions indicate. The use of cutting fluids may permit cutting speeds higher than those indicated. If Stellite tools are used, these speeds may be increased from 25-75%, depending upon the material being cut and the finish desired. If cemented carbide tools are used, speeds up to 250-300 f.p.m. are possible with the right type of tool. If carbon tool steels are used, the values given should be reduced by 50%.

A large number of types of steels are prepared in the form of bars for use in hand and automatic screw machines. For this work, the cuts are usually much lighter than those used in turret lathes, and for that reason the speeds are generally higher.

The machinability of many of these steels is improved by providing some non-abrasive constituent to break up the continuity of the ferrite. Sulphur is used commonly for this purpose. Steels containing sulphur are known as free cutting steels. For accuracy of dimensions, freedom from rolling mill scale, and improvement in machinability, cold drawing is practiced widely. Usually the hot rolled bars are not equal in machinability to the cold drawn product. Those alloy steels which work harden excessively in cold drawing are often machined in the hot rolled, annealed condition. Good free machining steel has low ductility and it also must possess a low order of work hardness. The tools should be ground so that the chips break up into small particles, rather than form into long coils. Table I lists free cutting steels used as cold finished bar stock, and gives the machinability rating based on the rating of S.A.E. 1112 steel as 100%. These speeds are suggested only for set-up purposes. They may be modified extensively to meet the requirement of the particular operation and cutting fluid used.

Cutting-Speed Tool-Life Relation in Turning—Many examples indicate that the analysis or condition of the steel cut influences the exponent n and the constant C in the cutting-speed tool-life equation $VT^n = C$, described in Part 2. In Parts 4 and 5, it is shown that the tool material and tool shape and cutting fluids also change this equation.

In turning, cast steel containing 25% chromium and 10% nickel, $\frac{3}{4}$ in. square tool bits were used, ground to 8° back rake, 14° side rake, 6° end clearance, 6° side clearance, 6° end cutting-edge angle, 15° side cutting-edge angle, and $\frac{1}{4}$ in. nose radius. In taking a cut 0.050 in. deep and 0.0255 in. feed per revolution, it was found that, when machining the bar as cast, the resulting equation was $VT^{0.088} = 46$, but when machining a corresponding bar after it had been quenched at 2000°F., the equation was $VT^{0.126} = 46$. These two curves are plotted in Fig. 3 and show a considerable

change in the value of the exponent merely through the change in structure. For a tool life of 1 min., the cutting speed for each curve is 46 f.p.m., but for a 60 min. tool life, the cutting speed for the heat treated bar is 25 f.p.m., and that for the "as cast" bar is 35 f.p.m.

Similarly, different bars of S.A.E. 3140 steel $2\frac{1}{4}$ in. in dia. were machined under identical conditions, with a cut 0.0625 in. deep by 0.0377 in. feed, and a high speed steel tool $\frac{1}{2}$ in. square ground to 6° back rake, 12° side rake, 6° front clearance, 6° side clearance, 13° end cutting-edge angle, 0° side cutting-edge angle, and $\frac{1}{4}$ in. nose radius. The bar was heat treated by heating to 1525°F., and after holding for 1 hr., quenching in oil, then tempered at 900°F. for 1 hr. to give a Brinell hardness range of 311-340, an elastic limit of about 150,000 psi., a tensile strength of about 165,000 psi., an elongation in 2 in. of about 16%, and a reduction of area of 55%, the resulting equation was $VT^{0.210} = 100$ as shown in Fig. 3. When a similar bar was annealed by cooling from 1575°F. after 1 hr. at heat, giving a Brinell hardness of 202-207, the resulting equation was $VT^{0.128} = 125$, shown in Fig. 3. The cutting speeds for the annealed bar are higher for all values of tool life than corresponding speeds for the heat treated bar.

Similarly, when machining S.A.E. 1340 steel with the identical tool and cut as outlined in the above, in the annealed condition, an equation was obtained of $VT^{0.200} = 244$. When machined in a spheroidized condition, the equation was $VT^{0.243} = 188$. These lines cross at a tool life of 90 min. The annealed bar permits higher cutting speeds for any tool life less than 90 min., but the spheroidized bar is better for greater values of tool life. Many other similar examples have proved this point.

The cutting speed for a 20-minute tool life, V_{20} , for an S.A.E. 1045 steel when cutting under a given cutting condition with high speed steel tools has a cutting speed of 150 f.p.m. for the annealed bar, about 139 f.p.m. for the cold finished bar, about 102 f.p.m. for the quenched and tempered at 1000°F., about 93 f.p.m. for the quenched and tempered at 600°F., and about 84 f.p.m. for the quenched in oil at 1520°F. This shows a wide variation in cutting speed because of the structure.

When cutting dry an S.A.E. 2340 steel annealed with a high speed steel tool of the 8-22-6-6-6-15- $\frac{1}{4}$ shape, the cutting speeds for 100-minute tool life varied as the size of chip was varied as follows:

A cut 0.0125 in. deep by 0.0125 in. feed gave a cutting speed of 176 f.p.m. and removed 33 cu. in. of metal per tool grind for a tool life of 100 min.

For the same tool life, when the cut was 0.035 in. deep by 0.0125 in. feed, the cutting speed was 120 f.p.m. and the cu. in. of metal removed per grind was 63.

When the depth was 0.100 in. and the feed was 0.0125 in., the speed was 72.5 f.p.m., and the metal removed per grind was 108.8 cu. in.

When the depth was 0.200 in. and the feed was 0.0125 in., the speed was 71 f.p.m., and the metal removed per grind was 213 cu. in.

For the same cross sectional area of cut as the 0.100 in. depth by 0.0125 in. feed, but with the depth reduced one-half and the feed doubled, the cutting speed for a 100-minute tool life was changed from 72.5 to 60 f.p.m., and the metal removed per tool grind was reduced from 108.8 to 90 cu. in.

Cutting-Force Relation in Turning—For a given steel and a turning, planing, or shaping tool, the cutting force in pounds (represented by its tangential T , radial R , and longitudinal L components) varies as the feed F and the depth of cut D , as indicated by the following equations:

$$T \text{ (tangential force)} = C_1 F^x D^y$$

$$R \text{ (radial force)} = C_2 F^x D^y$$

$$L \text{ (longitudinal force)} = C_3 F^x D^y$$

C_1 , C_2 , and C_3 are constants and x and y are exponents. Values of C , x , and y in this equation will vary with the steel or as the tool shape is changed.

The equations for the three components when cutting dry a low carbon steel fully annealed at 80 f.p.m. with a tool ground to 8° back rake, 22° side rake, 6° end clearance, 6° side clearance, 6° end cutting-edge angle, 0° side cutting-edge angle, and $\frac{1}{4}$ in. nose radius, are as follows: $T = 102,500 F^{0.80} D$; $R = 704 F^{0.80} D^{0.12}$; and $L = 12,600 F^{0.48} D^{1.25}$.

These equations, determined by O. E. Kraus, are shown to vary both in the value of the constants and exponents as the shape of the tool is varied, by changing the side and back rake angles, or the nose radius to such an extent that it is difficult to give a general formula.

F. W. Taylor⁴ determined a formula for tangential force on the tool when turning steel from 30-60 f.p.m., as follows: $T = C D F^{0.004}$.

The values of C ranged from 230,000 for soft, medium carbon steel, annealed to a tensile strength of 70,000-296,000 psi. for hard steel. Taylor's $\frac{1}{8}$ in. wide round nose tool was used having a back rake of 8° and a side rake of 14° .

The author has found the equation $T = CD^{.75} F^{.75}$ to hold in turning or planing an annealed S.A.E. 3150 steel. The value of the constant ranged from a minimum of 108,200 when cutting with a sulphurized mineral oil to a maximum of 128,200 when cutting dry. The high speed steel tool had 8° back rake, 14° side rake, 6° clearance, and 6° end cutting-edge angle, and $\frac{1}{2}$ in. nose radius. The setting angle was 90° .

It is evident that the change in material affects very widely the value of the cutting force. Fig. 4 shows the power due to the tangential cutting force when machining a variety of metals as compared to the resistance to cutting by milling and drilling.

Power, Torque, and Thrust in Drilling—Values of torque, thrust, and power were determined from drilling a normalized and annealed chromium-vanadium S.A.E. 6150 steel under various commercial conditions, as shown in Table II. The drills used were standard commercial taper shank drills of high speed steel, the points of which were ground carefully on a machine. For further details regarding drills and for detailed information when drilling other metals, see "Engineering Shop Practice."¹⁰ The feed of each drill corresponded as nearly as could be obtained on the machine to those generally recommended values shown in Table III. The actual r.p.m. is based on a peripheral speed of about 60 f.p.m. for all drill sizes, although torque and thrust are not affected by speed. One part of soluble oil to 16 parts of water was used in all tests.

In order to make it possible to determine the torque T in ft.-lb., the thrust B in lb., or power, for any other combination of drill dia. d in in. and feed f in in. per revolution, the following equations were determined: $T = C f^{.75} d^{1.4}$; $B = K f^{.75} d$. C is the constant for the material, drill, and

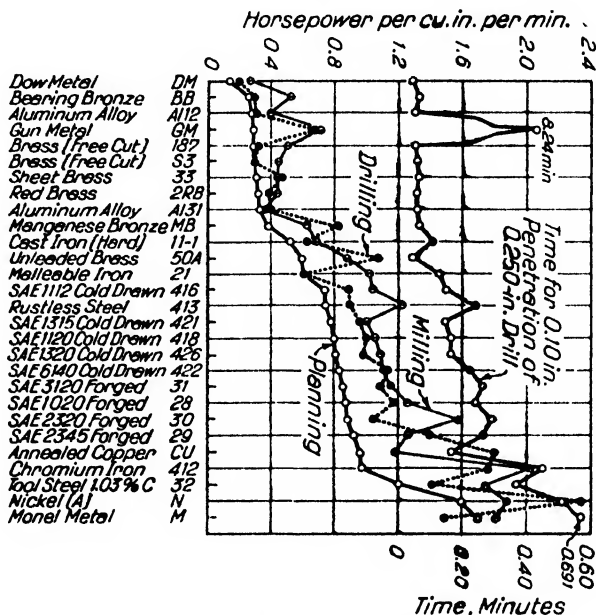


Fig. 4—Net values at the tool point of hp. per cu.in. of metal cut per min. for a variety of metals, as determined for drilling, milling, and planing under standardized conditions

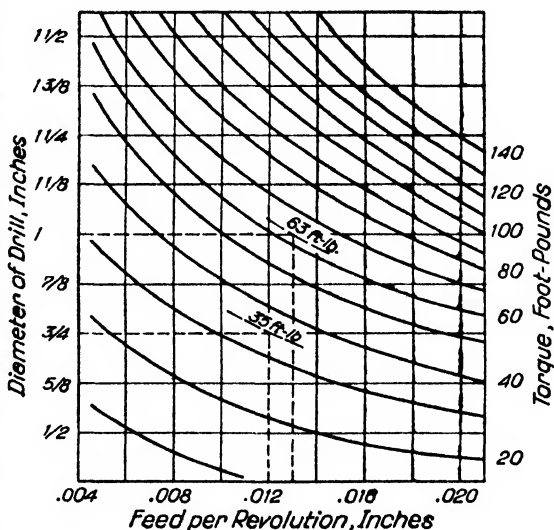


Fig. 5—Torque at drill point in drilling S.A.E. 6150 steel.

the following equations were determined: $T = C f^{.75} d^{1.4}$; $B = K f^{.75} d$. C is the constant for the material, drill, and

cutting fluid in the torque formula, and K is a similar constant in the thrust formula. When drilling S.A.E. 6150 steel having a Brinell hardness of 186, the formula becomes: $T_{6150} = 1,840 f^{.75} d^{1.5}$. The thrust formula becomes: $E_{6150} = 53,400 f^{.75} d$. The constants for torque and thrust are shown for a number of other steels in Table IV.

These equations are used to determine the torque and thrust for S.A.E. 6150 steel under any cutting condition. The torque and thrust for any drill diameter and feed may be determined graphically from Fig. 5 and 6, respectively. The torque for a 1 in. dia. drill operating at 0.013 in. feed is shown to be 63 ft.-lb. Similarly, the corresponding thrust is shown to be 1,820 lb.

Table IV also shows factors F_t and F_r for torque and thrust by which the torque and thrust, as determined from Fig. 5 and 6, can be multiplied in order to get the torque or thrust for any one of the other forged steels listed. To illustrate, it is desired to know the torque when drilling S.A.E. 2320 steel with a $\frac{3}{4}$ in. dia. drill operating at 0.012 in feed. From Fig. 5 the torque is shown to be 35 ft.-lb. for the S.A.E. 6150 steel. The torque factor for the S.A.E. 2320 steel is found to be 0.820 in Table IV. The resulting torque for the S.A.E. 2320 steel is equal to 35 times 0.820, or 28.7 ft.-lb.

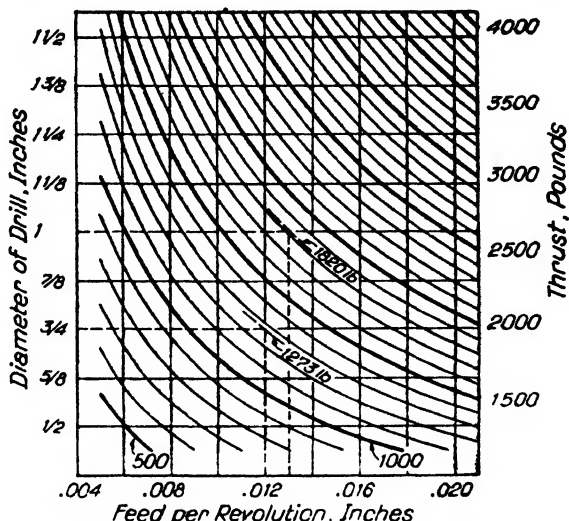


Table II
Torque, Thrust, and Power in Drilling an S.A.E. 6150 Steel. Normalized at 1650°F.
and Annealed at 1550°F. When Cutting With an Emulsion of 1 Part
Soluble Oil to 16 Parts of Water

Drill dia. in. <i>d</i>	Actual r.p.m. <i>N</i>	Feed, in. per Rev. <i>f</i>	Torque, lb-ft		Torque hp	Thrust, lb.		Thrust, hp.	Total Output, hp.	Input, kw.		Net hp.	Net Input, Efficiency, %	
			Test	<i>T</i> Formula		Test	<i>B</i> Formula			Gross	Tare			
½	444.5	0.009	14.0	13.43	1.185	725	678	0.00732	1.193	1.6	0.67	0.93	1.244	96
¾	368.0	0.011	22.3	23.4	1.562	838	990	0.00856	1.571	2.025	0.67	1.355	1.815	87
¾	299.7	0.012	34.3	34.8	1.957	1,269	1,273	0.01153	1.975	2.42	0.67	1.75	2.34	84
1	228.1	0.013	62.4	62.4	2.71	1,862	1,820	0.01394	2.724	3.176	0.57	2.606	3.49	78
1¼	175.1	0.015	110.8	104.0	3.694	2,430	2,520	0.01611	3.710	3.87	0.57	3.3	4.42	84
1½	149.0	0.015	143.3	144.0	4.07	3,000	3,020	0.01693	4.087	4.837	0.507	4.0	5.35	76.5

Table III

Speeds and Feeds Recommended for Drills of High Speed Steel in Various Metals
When Cut With a Suitable Coolant

Size of Drill, in.	Feed per Revolution, in.	Bronze, Brass	Alloy Steel Drop Forging	Cast Iron	Tool and Carbon Steel Drop Forgings	Mild Steel	Malleable Iron	Cast Steel	Hard Cast Iron
		300	50	140	Ft. per min.		90	40	80
					R.p.m.				
1/16	0.003	18,320	3,056	8,554	3,667	7,328	5,500	2,445	4,889
1/8	0.0035	12,212	2,038	5,702	2,442	4,884	3,666	1,628	3,258
3/16	0.004	9,180	1,528	4,278	1,833	3,667	2,750	1,222	2,445
1/4	0.0045	7,328	1,221	3,420	1,465	2,934	2,198	976	1,954
5/16	0.005	6,106	1,019	2,852	1,222	2,445	1,833	815	1,630
3/8	0.0055	5,234	872	2,444	1,047	2,094	1,570	698	1,396
7/16	0.006	4,575	764	2,139	917	1,833	1,375	611	1,222
1/2	0.0065	4,071	678	1,900	814	1,628	1,222	542	1,084
5/8	0.007	3,660	611	1,711	733	1,467	1,100	489	978
3/4	0.0075	3,330	555	1,554	666	1,332	1,000	444	888
7/8	0.008	3,050	509	1,426	611	1,222	917	407	815
1	0.0085	2,818	469	1,316	563	1,126	846	376	752
1 1/8	0.009	2,614	437	1,222	524	1,048	786	349	698
1 1/4	0.0095	2,442	407	1,140	488	976	732	326	652
1 1/2	0.010	2,287	382	1,070	458	917	688	306	611
1 3/4	0.0105	2,035	339	950	407	814	611	271	543
2	0.011	1,830	306	856	367	733	550	244	489
2 1/8	0.0115	1,665	277	777	333	666	500	222	444
2 1/4	0.012	1,525	255	713	306	611	458	204	407
2 1/2	0.0125	1,409	234	658	281	562	423	188	376
2 3/4	0.013	1,307	218	611	262	524	393	175	349
3	0.0135	1,221	203	570	244	488	366	163	326
3 1/8	0.014	1,143	191	535	229	458	344	153	306
3 1/4	0.015	1,017	170	475	204	407	306	136	272
3 1/2	0.016	915	153	428	183	367	275	122	244
3 3/4	0.016	833	139	389	167	333	250	111	222
4	0.016	762	127	357	153	306	229	102	204
4 1/8	0.016	705	118	329	141	282	212	94	188
4 1/4	0.016	654	109	308	131	262	196	87	175
4 1/2	0.016	610	102	285	122	244	183	81	163
4 3/4	0.016	571	95	267	115	229	172	76	153

Table IV

Constants for Torque and Thrust Formulas for Various Steels, and Factors for
Torque and Thrust Conversion When Using the Curves of Fig. 1 and 2

Steels, S.A.E. No.	Bar No.	Brinell	Torque Formula		Thrust Formula	
			C	Factor	K	Factor
1020	1	137	1,590	0.865	40,000	0.749
1045	2	159	1,590	0.865	42,000	0.786
2320	3	163	1,510	0.820	44,000	0.824
3120	4	143	1,510	0.820	39,000	0.730
3135	5	192	1,500	0.815	46,000	0.862
6150	6	187	1,840	1.000	53,400	1.000
3250	7	207	1,740	0.946	57,000	1.068
3140	8	196	1,550	0.843	50,000	0.936
2330	9	202	1,780	0.967	66,000	1.235
2340	10	207	1,840	1.000	65,000	1.218
6120	11	137	2,100	1.140	55,000	1.030
6130	12	156	2,000	1.087	56,000	1.049
6140	13	163	2,000	1.087	56,000	1.049
9250	14	202	1,800	0.978	63,000	1.180
Cr-Mo ¹	15	156	1,560	0.848	43,000	0.806
Cr-Mo ²	16	156	1,700	0.946	48,000	0.899
1095	19	154	2,180	1.184	69,000	1.291

¹0.35% carbon.

²0.28% carbon.

The total hp. developed at the drill point equals the hp. due to the torque plus the hp. due to the thrust as follows:

$$HP = \frac{2 \pi TN}{33,000} + \frac{B f N}{12 \times 33,000}$$

To illustrate, the 1½ in. dia. drill with a feed of 0.015 in., rotating at 175.1 r.p.m. (60 f.p.m.) when cutting S.A.E. 6150 steel, has a torque of 110.8 ft.-lb. and thrust of 2,430 lb. Substituting these values in the above equation, would give the total hp. as follows:

$$HP = \frac{2 \pi 110.8 \times 175.1}{33,000} + \frac{2,430 \times 0.015 \times 175.1}{12 \times 33,000} = 3.692 + 0.016 = 3.708$$

It is seen that the hp. due to the thrust is only 0.016 or only 0.44% of the total power developed, so for ordinary purposes the hp. output due to the thrust may be neglected. The thrust is of importance in design, however. Table II shows, however, that the efficiency of the machine as determined by dividing the input by the output is highest when using small drills operating at high speed with resulting low values of torque and thrust. Similarly, the efficiency is lowest when the torque and thrust are high, even though the speed of the machine is less. It has been found that torque and thrust are affected but little by a change in cutting speed. The power, however, is a direct function of the speed, as illustrated in the above.

The hp. per cu.in. of metal cut per minute is lower for larger values of feed and drill diameter. In drilling S.A.E. 6150 steel with a ½ in. dia. drill at 0.009 in. feed, a value of 1.443 is obtained. For drilling the same steel with a 1½ in. dia. drill at 0.015 in. feed, the hp. per cu.in. per minute is 1.075.

In another set of experiments¹¹ it has been shown that, when drilling several steels with 11 different types of cutting fluids, the equation for torque as given above holds for all steels. By varying the steels or the cutting fluids, only the constant is changed, as shown in Table V. The formula given for thrust above in connection with the S.A.E. 6150 steel holds roughly, but for more accurate work considering the variation in web thickness w of the drills of different sizes, a more accurate formula for thrust was developed as follows:

$$B = K f^{0.87} \left(\frac{d + w}{5} \right)^{2.13}$$

The performance of one cutting fluid on one steel does not indicate its relative performance on another steel. Actual values of torque and thrust when drilling an annealed S.A.E. 1035 steel with each of 11 cutting fluids are shown in Fig. 7 and 8. (Also see Cutting Fluids, Part 5.)

Table V shows the values of torque and thrust for standard ½ in. and 1½ in. dia. drills operating in each of 4 steels with 3 cutting fluids. The equations for torque and thrust and values of the constants also are indicated.

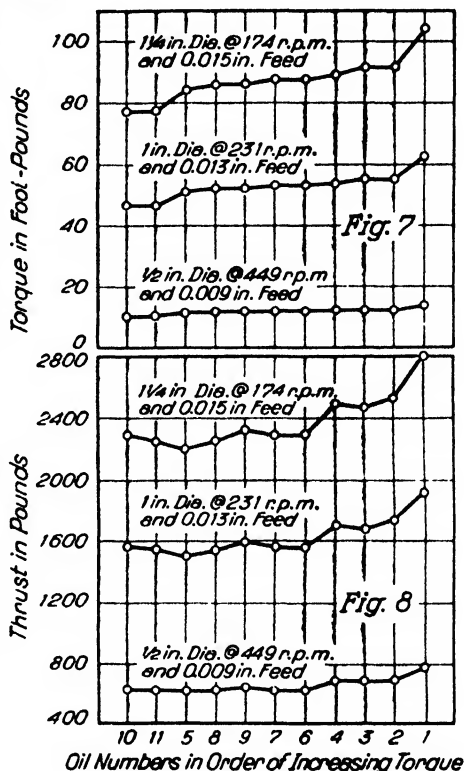


Fig. 7—The torque required to drill an annealed S.A.E. 1035 steel forging with various drill sizes operating at a speed of 60 f.p.m. and with cutting fluids as indicated: (1) Dry cutting; (2) 1½% borax in water; (3) 1 part soluble oil to 50 parts water; (4) 1 part soluble oil to 10 parts water; (5) No. 1 lard oil; (6) light mineral oil; (7) heavy mineral oil; (8) 10% lard oil; (9) mineral 5% oleic acid; (10) sulphurized mineral oil; and (11) sulphurized base oil blended 1-5 with light mineral oil.

Fig. 8—Thrust values required to drill the S.A.E. 1035 steel referred to in Fig. 7.

Table V

Torque and Thrust Values When Drilling Various Steels With Twist Drills Above ½ in. in Dia. and Three Types of Cutting Fluids

$$T = C f^{0.78} d^{1.8}$$

$$B = K f^{0.87} \left(\frac{d}{5} + \frac{w}{d} \right)^{2.12}$$

Material	Cutting Fluid	—½ in. Dia.— Drill ^a		—1¼ in. Dia.— Drill ^b		C	K
		Torque	Thrust	Torque	Thrust		
S.A.E. 1020, annealed.....	Dry	15.96	875	123.5	3,180	2,188	908,000
	1-50 emulsion.....	13.00	750	101.0	2,750	1,786	785,000
	Sul. oil.....	10.62	628	82.4	2,285	1,457	651,000
S.A.E. 1035, annealed.....	Dry	13.45	769	104.0	2,790	1,843	795,000
	1-50 emulsion.....	11.80	678	91.6	2,465	1,622	702,000
	Sul. oil.....	9.95	618	77.0	2,250	1,363	651,000
Carbon tool steel, annealed..	Dry	15.25	897	118.0	3,280	2,089	933,000
	1-50 emulsion.....	14.00	895	108.2	3,253	1,918	927,000
	Sul. oil.....	12.03	732	93.2	3,665	1,649	759,000
S.A.E. 3150, annealed.....	Dry	16.17	880	125.0	3,200	2,215	912,500
	1-50 emulsion.....	14.50	752	112.4	2,740	1,995	780,200
	Sul. oil.....	12.38	648	95.5	2,362	1,696	673,200
S.A.E. 1112.....	Dry	8.90	603	69.0	2,190	1,222	624,000
	1-50 emulsion.....	8.90	561	69.0	2,035	1,222	580,300
	Sul. oil.....	8.30	592	64.4	2,150	1,162	613,000

^aAt 0.006 in. feed and 449 r.p.m.

^bAt 0.015 in. feed and 174 r.p.m.

Table VI

Torque and Thrust Values for Drilling Various Steels Using a 1-16 Emulsion¹⁴

$$\text{Torque in ft.-lb.} = C f^{0.78} d^{1.8}$$

$$\text{Thrust in lb.} = K f^{0.87} d$$

Steel	—Values for the ¼ in. dia. drill— at 0.006 in. feed per revolution		C	K
	Torque in ft.-lb.	Thrust in lb.		
S.A.E. 1020, annealed.....	2.76	306	1,740	104,300
S.A.E. 1035, annealed.....	2.06	281	1,300	96,000
0.97% carbon tool, annealed.....	2.92	390	1,842	133,100
S.A.E. 3150, annealed.....	2.38	318	1,500	108,500
S.A.E. 1112, cold finished.....	1.58	217	1,000	74,100

Similar values for torque and thrust for drills ranging from ¼-½ in. in dia. when operating in the same steels with an emulsion consisting of 1 part soluble oil to 16 parts water are shown in Table VI. The equation for torque shown there for small drills is the same as that for larger drills shown in Table V. The equation for thrust for the small drills shown in Table VI is of a different form, as it does not account for variations in web thickness.

Part 4—Cutting Tools

A cutting tool is efficient according to the length of time per grind that it will cut at a certain speed under given condition (termed tool endurance), to the power consumed by the tool in removing the metal, and to the finish it produces. The smaller the cutting angle (the greater the rake), the more efficient is the cutting action, from a power viewpoint. The sharp lip will not stand up when cutting hard metals so well as the blunt lip. The greater the lip angle, the greater the reinforcement to withstand the cutting force, and to carry away the heat generated. The large rake tool induces the chip to flow over its face with less distortion, while the small rake tool pushes the metal off with excessive shear and compression. In general, a tool may fail: 1. By abrasion on the flank below the active cutting edge; 2. Because of the development by abrasion of a groove on its face behind the cutting edge, which wears forward to the cutting edge resulting in fairly sudden breaking off of the cutting edge; 3. By a combination of 1 and 2; 4. By spalling or crumbling of the cutting edge; and 5. By losing its hardness because of excessive heat generated at the cutting edge.

Types 1, 2, and 3 represent normal types of tool failure. Carbon tool steel tools usually fail by the first method when cutting steel and cast iron. High speed steel tools fail by the first method when cutting cast iron, but normally by method 2 or 3 when cutting steel, as illustrated in Fig. 2.

Factors entering into the performance of tools are as follows:

1. Composition; 2. Melting and casting practice; 3. Fabrication: Forged, ground from rolled bars, cast and sintered solid, tipped and bits; 4. Heat treatment; 5. Physical properties: Hardness, ductility, and hot hardness; 6. Tool form, such as profile of cutting edge, and various tool angles; 7. Tool sharpness; 8. Metallographic structure; 9. Tool setting.

Cutting Tool Materials—Cutting tools must be formed to meet the requirements of the material of which they are made. Cutting speeds and the size of the cut also must be in accordance with the tool material in order to get satisfactory commercial tool life. Cutting tools are commonly made of carbon tool steel, finishing steel, high speed steel, Stellite, cemented carbide, and diamonds. Carbon tool steels are used to some extent where light cuts at comparatively low speeds are permissible, in screw machines on free cutting materials where the tool is well cooled, or where formed tools are stocked for infrequent use. By far the greater majority of tools being used are made of high speed steel. The 18-4-1 type of high speed steel is the most generally used type for all around work. It is uniform in performance. The 18-4-2 type steel generally gives slightly better performance than the 18-4-1 type. The 18-4-3½ type of high speed steel is coming into favor for heavy duty work. Molybdenum steels, such as 8-4-1 and 8-4-2, also are coming into general use where high speed steels are involved. The cobalt high speed steels give up to 25% greater production for certain heavy duty jobs.

Stellite and cemented carbide tools are nonferrous in character. These alloys are cast or sintered to shape, and finally ground. Neither can be forged or heat treated, and both usually are used in the form of tips welded onto the end of heavy steel shanks. Both Stellite and cemented carbide are less ductile than high speed steel and serve best when cutting materials which are abrasive in character. They must be ground with less clearance and rake so as to provide a greater lip angle to support the cutting edge. Both should be supported rigidly so as to avoid bending

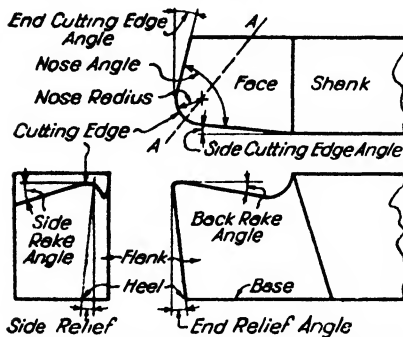


Fig. 9—Nomenclature of a ground, straight cutting edge, right-cut, straight-shank, single-point tool. (A.S.A. standard.)

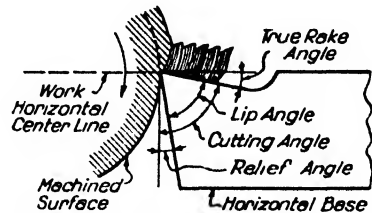


Fig. 10—A section through the active cutting edge A-A of Fig. 9 showing true nomenclature.

or chattering. Terminology applied to a ground tool is illustrated in Figs. 9 and 10, which represent a typical high speed steel, shank-type tool.

Performance of Tools—When cutting a given steel, the analysis or treatment of the high speed steel tool, as well as its geometric shape, have a bearing on its performance. A series of cutting-speed tool-life tests was run with each of four high speed steel tool bits, two of which were of the regular 18-4-1 type of high speed steel, the third was a cobalt high speed steel, and the fourth a molybdenum high speed steel. When ground to a specific shape for turning dry annealed S.A.E. 2345 steel, individual equations were obtained, indicating that the constant, as well as the exponent, of the tool life equation is subject to change because of the tool material.

Influence of the Tool Shape on Tool Life—For a 60 min. tool life, the cutting speed is increased 125% as the radius of the nose of the tool is increased from

0- $\frac{1}{4}$ in.¹⁴ Increasing the side cutting angle similarly shows a great increase in cutting speed for the same tool life. Frequently with side cutting angles greater than 30° on deep cuts where deep thin chips are taken, chatter is likely to occur. This chatter may be eliminated by changing the cutting fluid, the cutting speed, the size or shape of cut, and preferably reducing the side cutting-edge angle. The speed for a 60 min. tool life is increased 55% as the side cutting-edge angle is increased from 0-60°. The side rake angle similarly shows an increase in cutting speed for any given tool life, but when cutting an annealed S.A.E. 2335 steel, the maximum speed was reached for a side rake angle of 22°. However, a 70% increase in cutting speed was obtained by increasing the side rake angle from 0-22°. When cutting soft steel, the greatest tool life for a given speed is obtained when the tool is ground as follows: 8° back rake, 22° side rake, 6° clearance, 6° end-cutting-edge, 45° side cutting-edge angle, and $\frac{1}{4}$ in. nose radius. For harder steel, the side cutting-edge and side rake angles should be reduced.

Influence of Tool Shape on Cutting Force—When taking a cut 0.100 in. deep with a feed of 0.0125 in. in an 0.61% carbon steel of 207 Brinell and 99,000 psi., with a basic tool ground to 8° back rake, 14° side rake, 6° end cutting-edge angle, 15° side cutting-edge angle, and $\frac{1}{4}$ in. nose radius, the cutting force varied as follows: As the nose radius is increased from 0- $\frac{1}{4}$ in., the tangential force remains practically unchanged at 395 lb.; the longitudinal force falls from 185-95 lb.; and the radial force is increased from 25-150 lb. As the side cutting-edge angle is increased from 0-60°, the tangential force remains practically constant at 395 lb. It falls off slightly for the 30 and 45° angles. The longitudinal force is gradually reduced from 173-90 lb., and the radial force is increased from 48-180 lb. As the side rake angle is increased from 0-40°, the tangential force drops from 440-335 lb., the longitudinal force drops from 245-98 lb., but the radial force remains practically constant. A change in back rake angle from 0-16° produces only a slight reduction in tangential and longitudinal forces, but causes the radial force to drop from 75-0 lb.

As the cutting speed is varied for an otherwise given cutting condition, all components of the cutting force remain practically constant at the higher speeds. At the very low speeds, all values of components vary. The temperature between the tool and work, as determined with a thermocouple, rises rapidly until a speed of between 10-20 f.p.m., depending upon certain variables, is reached, after which it increases in direct proportion to an increase in speed.

Cutting Fluids—See the article in this Handbook on Cutting Fluids for Machining.

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Abrasive Wheels for Grinding Steel

By A. Rousseau*

Introduction—Grinding has not yet been established as an exact science. Although much progress has been made in that direction during the past few years, it must still be considered an art. It is not possible to determine by mathematics, nor by any other scientific means, the correct wheel for a given operation. Tables and charts based on empirical data and experience are of considerable value in making first selections, but these must be used with judgment, and with an understanding of the general characteristics of grinding wheels and of the effect of certain variable factors which are governed by the work and operating conditions.

Grinding Wheel Characteristics—The characteristics of a grinding wheel are dependent on several variables which are under the control of the wheel manufacturer. The principal variables are the following:

1. Kind of abrasive used.
2. Size of abrasive grains (coarseness).
3. Process by which wheel is bonded.
4. Grade of hardness.

1. There are many kinds of abrasives, known by various trade names, but they can all be roughly classified in the two general groups, aluminum oxide and silicon carbide, each of which is adapted to certain types of work.

2. Approximately 20 more or less standard grain sizes, or degrees of coarseness, are in common use. These grain sizes are usually designated by a numeral which indicates approximately the number of meshes per linear inch of a screen through which the grains will pass. The coarseness of a wheel can be still further varied by using certain combinations of two or more "straight" sizes.

3. Five important processes of bonding the abrasive grains are in common use—vitrified, silicate, rubber, resinoid, and shellac. The characteristics of these processes can be still further controlled by varying the methods of mixing and molding.

4. Vitrified and silicate wheels can be made in about 18 grades of hardness. Most manufacturers designate these grades by letters, using the first letters of the alphabet for the softer grades and the last letters for the harder grades. A few wheel makers run their scale in the opposite direction, while still others use special code arrangements.

Rubber, resinoid, and shellac wheels can be made in about 8 or 10 grades, but here again there is no standard method of designation.

Another method of varying the grinding characteristics of a wheel is by controlling the structure or grain spacing. Wheels can thus be made dense or more open depending upon the requirements of the operation. Surface grinding, for instance, calls for wide grain spacing or "open structure," while cylindrical grinding usually calls for denser structure.

Work and Operating Conditions—The conditions or factors pertaining to the work which are of prime importance in selecting the grinding wheel are the following:

1. Material to be ground.
2. Amount of material to be removed and degree of accuracy.
3. Finish required.
4. Arc of contact.
5. Type of grinding machine.

The effect of these conditions on the grinding operation can be varied greatly by other factors which are, to a certain extent, under the control of the user. The most important of these variable factors are the following:

1. Wheel speed.
2. Work speed (pressure, if off-hand grinding).
3. Condition of machine.
4. Skill of workman.
5. Use of coolant or lubricant.

*Norton Co., Worcester, Mass.

Selection of Grinding Wheel—Charts 1 to 4 show in a general way the factors and rules which affect the selection of the various constituents of a grinding wheel; namely, the abrasive, the grain size (coarseness), the process of bonding, and the grade of hardness. In using these charts it should be borne in mind that they are not laws, but merely empirical rules and as such are sometimes subject to modification to suit individual conditions.

The manufacturers of grinding wheels have classified tables which show the application of these rules to specific problems frequently encountered in the grinding of steel. In these tables are designated the grain, grade, abrasive, and process used.

Causes and Prevention of Checking and Cracking—The checking or cracking of hardened steel pieces after grinding may be traced to either the heat treatment or the grinding operation.

Some of the sources of trouble in the first mentioned cause are too high heats, forcing heats, and carelessness in tempering.

Improper use of grinding wheels and improper methods of grinding also cause difficulty. In some instances it will be found that the wheels used are too hard or that too deep cuts are taken in an attempt to get increased production. Often the work is ground with an inadequate supply of cooling solution, or the solution is not directed to the point of contact. All of these factors lead to the generation of considerable heat which cannot be readily dissipated. This heat is usually sufficient to cause enough unequal expansion between various points on the surface being ground to result in checking.

The methods of eliminating this difficulty depend upon the conditions surrounding any particular job. Some of the more common remedies are:

1. Softer wheels—lighter cuts—quicker passes.
2. Greater flow of cooling solution at the point of contact.
3. Slower wheel speed.
4. Increased work speed.

To prevent checking when surface grinding hardened steel with some types of machines, the following preventative methods are used:

1. Wheels with narrower rim thickness.
2. Additional supply of cooling solution.
3. Finer grained wheels.

This last mentioned factor has solved the trouble in several instances. Several tests have been made where a coarse, relatively soft wheel burned the work and a finer wheel in approximately the same grade did not burn. An explanation of the reason for this may be necessary, as coarser and softer wheels are ordinarily recommended to overcome a burning or hard wheel difficulty.

When surfacing hardened steel with a vertical spindle machine using a cup wheel, the depth of cut permissible is naturally limited. The feed that can be

Chart I
Factors Affecting the Selection of the Abrasive

Physical properties of the material to be ground.....	{	Use aluminum oxide grinding wheels for materials of high tensile strength.	Carbon steels
			Alloy steels
	{	Use silicon carbide grinding wheels for materials of low tensile strength.	High speed steels
			Annealed malleable iron
			Wrought iron
			Tough bronzes
			Tungsten
			Gray iron
			Chilled iron
			Brass and bronze
			Aluminum and copper
			Marble
			Granite
			Pearl
			Rubber
			Leather

taken is governed absolutely by the ability of the abrasive grains to penetrate the surface of the metal. It is difficult to force large grains of abrasive into hardened steel. They can only penetrate a small percentage of the over-all size of the grain, not enough in fact to pull the grains out of the wheel face. As a result they become dull, do not cut, slide over the surface of the steel, and then when a little more feed is applied they start to burn the work. With a fine grained wheel the depth of cut more nearly equals the size of the grains and that allows them to be pulled from the wheel before they become too dull to cut any further. Also in a finer wheel there are more grains to a square inch of cutting surface, hence the material removed per unit of time is greater.

Chart II

Factors Affecting the Selection of the Grit

- | | |
|--|--|
| A. Amount of material to be removed.... | { Use coarse wheels for fast removal of stock.* |
| B. Finish desired..... | { Use fine grain for fine finish. |
| C. Physical properties of material to be ground. | { Use coarse grain for ductile materials and finer grain for hard, dense, and brittle materials. |

Chart III

Factors Affecting the Selection of the Grade (Degree of Hardness)

- | | |
|--|---|
| A. Physical properties of material to be ground. | { Use hard wheels on soft materials and vice versa. |
| B. Arc of contact..... | { The shorter the contact, the harder the wheel should be. |
| C. Wheel speed and work speed | { The higher the ratio of work speed to wheel speed, the harder the grade should be and vice versa. |
| D. Condition of grinding machine... .. | { Machines in poor condition require harder wheels than machines in good condition. |
| E. Skill of operator..... | { Skillful operators can use softer wheels than unskilled—softer wheels mean more economical production.
Piece-work grinding usually requires harder wheels than day work. |

Chart IV

Factors Affecting the Selection of the Process

- | | |
|-----------------------------|--|
| A. Dimensions of wheel..... | { Wheels subjected to bending strains should be made by resinoid, shellac, or rubber process.
Extremely thin abrasive saws must be made by the resinoid, shellac or rubber process.
Wheels over 42 in. in dia. are usually made by the silicate process. |
| B. Rate of cutting..... | { Use vitrified wheels for most rapid cutting at speeds under 6,500 s.f.p.m.; use resinoid, or rubber wheels at higher speeds. |
| C. Finish desired..... | { Use shellac or rubber wheels for highest finish, where rapid production is not a factor.
Use silicate wheels for cutlery. |

*An exception to this rule is made in the case of very hard or tough steels, especially when surface grinding. On such work finer wheels sometimes remove stock more rapidly than coarse ones.

Cemented or Sintered Hard Carbides

By A. MacKenzie*

General—Cemented carbide products are customarily produced by mixing powdered constituents consisting of one or more metallic carbides with a lower melting point cementing or binding material. The mixed powders are pressed in a wide variety of shapes, usually in steel molds under hydraulic pressure. To facilitate handling and forming, the pressed pieces may be "presintered," in which condition they can be shaped with steel tools. After such shaping, final hardness is obtained by heating to a higher temperature. Both sintering operations are made in a furnace having a nonoxidizing atmosphere.

Powdered Constituents—The powdered constituents in general use are monocarbides of tungsten, tantalum, and titanium, or combinations of these. Cobalt and nickel are the most common lower melting point cementing agents. In some combinations, minor percentages of other metallic substances are added or are present as contaminations.

Cemented tungsten carbide, with cobalt as the binder, is—and has been—the predominating combination. The cobalt content varies in accordance with the desired combination of properties. Combinations of tantalum carbide, tungsten carbide, with or without tungsten metal powder, and with nickel as the binder, also have desirable properties in the opinion of Philip M. McKenna.

Technique—Carbide—The carbides are ordinarily formed by adding carbon in the form of lampblack to the powdered metal or oxides, then heating in a suitable atmosphere to temperatures usually ranging from 1500-2400°C. The proper combination of time and temperature for carbon absorption is different for each element.

The carbide, before mixing with the cementing material is in a finely divided state with varied size of particles, a maximum particle size of 15 microns being usual.

The Cementing Material and Its Introduction to the Carbides—The prime cementing material, cobalt, is produced in powder form, generally by reduction at low temperatures from the oxide.

Intimate mixing of the metallic powder, so produced with one or more of the carbide powders, is attained by ball milling. One purpose of milling is to coat all carbide particles with a film of cementing material. The time of ball milling varies for each type of product, but as a rule it increases as the binder content decreases.

In some processes, it is reported that the ball mill lining is of the same material as the final binder in the cemented carbide, and that the binder is obtained from this lining. In such processes, the time of milling is so established that the proper amount of binder is incorporated during the milling period.

Pressing—At this stage in the process, the powders are given definite form. The usual pressing operation is one in which the powder is placed in a hardened and ground steel mold, then compressed under hydraulic pressure. Varying pressures are used, but the common practice is from 15-30 tons per sq. in.

The practice is to press a slab or ingot approximately 1-1½ in. wide by 7-11 in. long, and in various thicknesses.

In special cases, particularly wire drawing dies, molds are made to press specific sizes and shapes.

In all cases, with this process, the molds and powder are handled at room temperatures. In the art, the process is known as the *cold press method*.

Another process, not now widely used for production purposes, is known as the *hot press method*. This involves pressing and sintering the powder simultaneously. This process uses carbon molds inserted between electrodes and heated by resistance. The pressure is applied simultaneously through carbon plungers during the heating cycle. These carbon molds can be machined to predetermined shapes, but, in the majority of cases, can only be used for pressing one piece. This method is not as amenable to control as the cold press method, and is more costly.

Presintering or Semisintering—These terms are in use to indicate the heating

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step in the process which slightly hardens the pressed pieces so they can be handled and shaped.

The pressed pieces, as removed from the molds, are placed on graphite slabs and put into electric muffle furnaces with suitable atmospheres and at temperatures of about 850°C.

Forming—On removal from the presintering furnaces, the pressed pieces can be turned in lathes, or cut to definite shapes or forms, with ordinary tools. At this stage, the material might be classed as chalk-like, although much more abrasive.

The density of semisintered cemented tungsten carbide material is about 9, while the sintered material will run up to or above 15.

A substantial shrinkage in volume takes place during the final sintering operation, so in forming or shaping this shrinkage must be allowed for.

Sintering—This is accomplished by heating through a definite cycle under controlled atmospheric conditions. The product, in this step, attains its final physical state.

For sintering in an electric furnace, the formed pieces may be placed in carbon boats and passed through the furnace under definite time and temperature control. The time and temperature will vary, depending on the composition of the material being sintered, and the size of the mass.

For the furnace atmosphere, hydrogen is in general use, although other gases having nonoxidizing characteristics are, and can be, used. Vacuum is sometimes resorted to, especially with combinations rich in tantalum carbide.

The phenomena causing change in dimension and physical characteristics during the sintering operation are complex; and not completely understood.

Wyman and Kelley¹, reporting on their study of the action of the cementing material in cemented tungsten carbide, concluded "that the binding constituent in the cemented tungsten carbide materials usually reaches the liquid state during the final sintering operation, at which time it consists of tungsten carbide dissolved in cobalt. It is believed that upon solidifying this cobalt-rich cementing material remains as a solid solution of tungsten carbide in cobalt."

S. L. Hoyt² in a description of the forces set up during sintering, suggests that "the formation of a liquid phase, which wets the surface of the carbide particles, sets up tensile forces of surface tension that tend to pull these particles together." There are known instances of approximately a 2 in. total linear shrinkage starting from a 16 in. length.

Minute porosity is encountered in most cemented carbides. Some reasons are: Entrapped gas; impurities; improper rate of heating; improper particle distribution; or improper pressing technique. Much progress in eliminating these defects has been made by the various manufacturers through better raw material and process control.

Properties of Cemented Carbides—The physical properties vary with the different combinations of constituents. In addition, physical properties for the same combinations, can be, and are, changed by processing.

The values listed in Table I are representative of specific compositions and processes only. They do not necessarily represent the ultimate properties in identical combinations. The various values given for each combination are not necessarily taken from the same specimen.

According to S. L. Hoyt, the modulus of elasticity on a 13% cobalt sample has been determined by A. L. Kimball, of the General Electric Research Laboratory, to be 79,000,000 psi., with an accuracy of about 0.5%. This is higher than any other known material, and is well above tungsten, which has a modulus of 60,000,000 psi., and which, in turn, has twice the modulus of steel. On compositions of high tantalum carbide content the Research Laboratory of the Vanadium Alloys Steel Co., reports a modulus of elasticity of 56,000,000.

S. L. Hoyt states that J. V. Emmons, of the Cleveland Twist Drill Co., determined the torsional modulus of elasticity on a 13% cobalt sample as being 17,250,000 psi., and of highspeed steel as being 8,150,000. The highspeed steel was hardened at 2350°F., after 30 seconds and drawn at 1040°F. for 30 minutes. The size tested in each case was 4% in. long by 0.310 in. diameter.

Table I
Properties of Cemented Tungsten Carbide

Cobalt, %	3	6	9	13	20
Density g. per cc. at 21°C.....	15.04	14.82	14.56	14.10	12.54
Modulus of rupture as determined by transverse strength in psi.....	125,000	205,000	250,000	300,000	.....
Rockwell A hardness on C scale with 60 kg. load	91.0-93.0	90.0-92.0	88.5-91.0	87.0-89.5	.....
Vickers Brinell number.....	1380 ^a	1450 ^a	1365 ^b	1255 ^b	755 ^b
Shore monotron No.*.....	190	145	.....	130	.....
Electrical resistance, microhms per cm. cube at 20°C.	21.3	21.1	22.3	19.6	29.2
Temperature coefficient of resistance, for interval 20-30°C.	0.0047	0.0045	0.0043	0.0044	0.0038
Coefficient of thermal expansion, per °C. over range 20-400°C. ....	.....	.....	.....	6.0x10 ⁻⁴	.....
Compressive strength in psi. ^d	(4½% Co.) 890,000	680,000	.....	540,000	.....

*10 kg. load.

^aFigures are the load to produce a penetration of 9/5000 in. The 190 reading was for a 6% Co. pressed hot, while the 145 and 130 readings were for 6% and 13% Co.

^b30 kg. load.

^dDr. P. W. Bridgman, Harvard University.

The thermal conductivity of a 13% cobalt sample has been determined by H. A. Robinson at the Massachusetts Institute of Technology, and found to be 0.652 watts per cm. per sec. per °C. with a deviation of ± 0.025 . This conductivity is about 50% greater than that of tool steel. The thermal conductivity of a tantalum carbide composition (78% TaC) is about 0.224 watts per cm. per sec. per °C. as determined by William Newcomer of the Vanadium Alloys Steel Company Research Laboratory.

Cemented Tantalum and Titanium Carbides—Commercial cemented tantalum grades range from tantalum carbide with a binder to grades having varying percentages of tantalum carbide and tungsten carbide plus the binder.

For certain applications, the commercial grades of cemented tantalum carbides have advantages over cemented tungsten carbide grades in resistance to certain types of corrosion.

In addition, cemented tantalum carbide has a lower coefficient of friction against steel than cemented tungsten carbide. This is a beneficial characteristic in the application of the material to steel cutting, as the heat generation is lessened and the resistance to loading, or cratering on the cutting edge, is appreciably increased.

Cemented carbides containing titanium carbide are predominately, in so far as weight is concerned, tungsten carbide with the titanium carbide as a minor, though potent, constituent. Grades containing titanium carbide have been developed and are being used for steel cutting applications.

Properties of Tantalum and Titanium Carbide—Physical properties of representative combinations of the cemented tantalum carbide grades and the cemented titanium grades are listed in Table II.

Product Control Methods—Hardness, density, strength, and microscopic examination are used for production control and experimental evaluation. In addition, field tests, under actual operating conditions, are extensively used for determining the merits of new combinations.

Hardness Determination—The most commonly used method is the Rockwell test. The manufacturers of cemented carbides have established an arbitrary standard using the standard diamond penetrator and reading on the C scale, but with the 150 kg. major load removed, using instead the 60 kg. major load. This new standard has become known as the "A" scale. No mathematically exact conversion figures from the Rockwell A to the Rockwell C scale exist.

To assure proper hardness readings on cemented carbides requires careful preparation of the sample. All surfaces on which readings are to be taken should be ground, and preferably lapped, parallel to the ground, and lapped bottom surface. It is difficult to obtain proper readings on cemented carbide parts while brazed to, or held, in steel supports. Hardness values for a given carbide content usually increase as the binder content decreases.

Table II
Properties of Tantalum and Titanium Carbides

Combination	Hardness, Rockwell A Scale	Density g./cc.	Modulus of Rupture, psi.
Predominately tantalum carbide plus 13% binder.....	87.0	13.55	175,000
Equal amount of tantalum carbide and tungsten carbide plus 13% binder	87.2	13.65	250,000
Predominately tungsten carbide plus tantalum carbide and 13% binder	87.5	13.91	275,000
80% tantalum carbide, 12% tungsten metal, 8% nickel.....	88.4	.....	250,000
75% tantalum (Columbium) carbide, 13% tungsten metal, 13% nickel	88.3	.....	275,000
72% tantalum (Columbium titanium) carbide, 20% tungsten metal, 8% nickel	91.0	.....	185,000
Predominately tungsten carbide plus titanium carbide and 13% binder	89.8	12.80	250,000
Predominately tungsten carbide with increased amount of titanium carbide and 13% binder.....	90.0	11.95	240,000
Predominately tungsten carbide with increased amount of titanium carbide and 13% binder.....	90.0	10.10	180,000

Hardness values should not be used as indicators of cutting tool or die efficiencies, especially where a comparison of one carbide combination with another is being made. Under properly controlled manufacturing conditions, little or no variation in hardness for a given grade should be encountered, so this method is valuable for control purposes.

Density Determinations—This test is the usual water displacement one of weighing the piece dry and then in water, using an analytical balance, and calculating the density from the difference in weight. This acts as a check on constituents and porosity against previous standards or theoretical densities.

In the cemented tungsten and tantalum carbide combinations, the density increases as the binder decreases. With combinations having sufficiently high titanium carbide, the density will decrease as the binder decreases.

Strength—The hard cemented carbides possess little or no ductility. The strength is measured by calculating the modulus of rupture or maximum stress in the outermost fibre by means of test bars ruptured transversely. Values as high as 400,000 psi. for 13% binder, and 280,000 psi. for 6% binder, have been attained. Comparable readings on high speed steel have been 400,000 psi., and on superhigh speed steel up to 600,000 psi.

Microscopic Examination—Samples of cemented carbides are examined and photographed at magnifications up to 1500.

Samples of cemented carbides may be prepared for microscopic examination by first grinding with a silicon carbide or a diamond impregnated wheel, then lapping with No. 5 diamond dust or a fine diamond impregnated wheel, and then polishing with a fine diamond dust.

An etching solution containing equal parts of a 10% solution of KOH (Potassium Hydroxide) and a 10% solution of $K_3Fe(CN)_6$ (Potassium Ferricyanide) is one of the solutions in use. The length of time for etching is from 3-5 min.

Application of Cemented Carbides—The use of cemented carbides can be divided into three classes: (a) As a die material; (b) as a cutting tool material; and (c) as a wear and corrosion resistant material.

(a) **Die Applications**—These materials are generally used for the drawing of bars, rods, wire, and tubing, and in a wide variety of sizes and shapes. Extrusion, sizing, deep drawing, forming, eyelet, and burnishing dies, as well as mandrels, are also widely used.

There are few restrictions for this die material, except size, as it is used with many materials and for many operations. Some examples may be listed as follows:

For the cold and hot drawing and extrusion of wire, bars, and tubing from

high and low carbon steels, alloy steels, stainless steels, tungsten, molybdenum, nickel, and nickel alloys, aluminum alloys, copper, brass, zinc, and precious metals. For the extrusion and sizing of bolt and screw stock. For the drawing and forming of eyelets, lamp bases, metal radio tubes, shells, and ferrules. For nut burnishing.

(b) *Cutting Tools*—Cemented carbides are used for machining all types of metallic parts made from cast iron, aluminum, brass, bronzes, copper, babbitt, zinc, and all their alloys. In addition, they are extensively used in machining nonmetallic materials and resinous products such as hard rubber, celluloid, Bakelite, asbestos fibre, casein, vegetable ivory, porcelain, linoleum, catalon, Masonite, wood, and carbon.

Steel cutting with cemented carbides presents more hazards because chip or cut pressures are generally much higher than with cast iron. A phenomenon associated with these increased cut pressures, and which leads to early failure, is *cratering* or *loading*. This is the result of fragments from the chip welding to the tool material and causing minute particles to break out. In time, as the crater increases, the cutting edge breaks away and the tool fails.

Tantalum carbide and titanium carbide compositions resist this cratering much better than cemented carbide compositions containing only tungsten carbide and a binder.

Progress has been made in steel cutting with these cemented carbides. Certain types of application, such as precision boring of automotive and other type connecting rods, as well as the many applications involving light finishing cuts on the harder types of steel are successfully carried out. The number of applications on steel cutting are definitely increasing.

Types of Tools Used—A partial list of the many types of tools that are being tipped with cemented carbide is given below. The size of single purpose tools in the various classifications will vary from $\frac{1}{4}$ in. square or round up to 3 and 4 in. square.

Single point turning, boring, facing, chamfering, and planer tools

Grooving tools for straight and form grooving.

Form tools—flat and circular.

Blades for inserted type milling cutters, adjustable reamers, and saws

Drills, both flat and spiral.

In addition, multiple tipped solid shank tools are in use such as—

End mills	Core drills
Side mills	Spotfacers
Hollow mills	Counterbores
Profiling cutters	Valve seating tools
Multiple tipped form and grooving tools	Broaches
Step drills	Saws
Reamers of many types	

Although each job has its peculiar characteristics and no one value can be given which covers a whole class of work, a recent report of the Subcommittee on Metal Cutting Materials of the A.S.M.E.³ indicates average production increases through the use of cemented carbides as being:

Cast iron—10-200%, the average being about 60%.

Steel—Increases of from 10-80%, with the average about 35%.

Aluminum, brass, bronze, special alloys, and other nonferrous materials indicated, increase from a minimum of 15% to a maximum of 500%.

The same report indicated saving in cost of production as follows:

Cast iron—from 5-75%, averaging about 28%.

Steel—from 5-50%, averaging about 22%.

Other materials—from 20-75%, averaging between 20 and 40%.

The same report also has the following to say about cutting speeds:

"Cutting speeds, feeds, and depths of cut being used successfully, varied greatly. About all that it is possible to do here is to give an idea as to the average speeds being employed on various materials.

"On cast iron roughing cuts, the cutting speeds ran all the way from 55 ft.

per min. up to 500 ft. per min., the average being about 175. On finishing cuts, the speeds were from 70-580 ft. per min., the average being 245 ft. per min.

"On brass and bronze, the cutting speeds ranged from 150-2,250 ft. per min., average about 510. On soft steels, the speeds ranged from 95-400 ft. per min., average about 200. On hard steels, the speed range was 40-300, average 135. The tendency was toward high speeds and light feeds in general."

Suggestions for Handling Cemented Carbide Tools—A few general suggestions on handling of cemented carbide tools together with general recommended cutting angles follow:

(1) *General Handling*—When handling cemented carbide tools, care should be taken not to abuse the carbide tip. Do not drop the tool or tap the tip with a hammer while setting up. Carbide tools can stand a certain amount of abuse, but consideration should be given at all times to the fact that cemented carbides are hard, and, usually, easier to break than steels.

(2) *Setting Up*—In setting up a job, the customary procedure may be followed in general. There are, however, certain factors which must be observed to get the greatest performance from cemented carbide tools. Briefly, these are as follows:

- (a) Keep the tool overhang at the absolute minimum which will allow the tool block to clear the work.
- (b) Use the proper size tool for the job. Do not use small bits and tool holders for large work.
- (c) Use only the tool holders specially developed for cemented carbide tools. These are designed to keep the base of the tool on a horizontal plane.
- (d) Set tools to cut on the center line of the work.

(3) *Depth of Cut*—

- (a) In all cases, the depth of cut should never exceed the length of the cemented carbide tip. In other words, all contact with the work should be against the cemented carbide tip and not permitted to extend into the steel shank.
- (b) In general, on jobs where a large amount of stock is to be removed, the capacity of the machine, rather than limitations of the cemented carbide tool, usually govern the depth of the cut.
- (c) When machining castings with tough scale, cemented carbide tools can take a light cut just under the scale and stand up for economical periods. Because of this, castings can be made closer to finished size than when using steel tools.
- (d) Where the thickness of metal to be removed is not great, frequently the rough and finish cuts, or rough and semifinish cuts may be combined when using cemented carbide tools.
- (e) When starting cut on irregular pieces, use care to avoid excessive depth of cut.

(4) *Feed*—When starting cemented carbide tools on a new job, it is usually desirable to start with a $\frac{1}{2}$ reduction of feed ($\frac{1}{2}$ less than previous practice with high speed steel tools) and increase until the most economical feed is reached. Speeds, of course, must be considered when adjusting feeds. (See *Speed* below.) In general, the following should be observed: (a) Always disengage feed before stopping work (or if work is stalling). (b) In starting on irregular pieces, use care to avoid excessive feed.

(5) *Speed*—In general, it is suggested that you start cemented carbide tools at approximately double the speed used for high speed steel tools on the same application. From this point on, the most economical speed will depend upon the condition of the machine tool, output requirements, the relation of the operation to subsequent and preceding operations, the grinding and the set up time, and the number of pieces obtainable between grinds. It is obviously impossible to set down any definite figures of exact speeds recommended, due to variable factors on every job and variations in the material itself to be machined. But with the knowledge that speed can be increased greatly with cemented carbide tools, and in most cases at least 100%, satisfactory practice on the particular requirements can be quickly established.

(6) *When to Use Coolants*—Use of cemented carbide tools does not alter the rule for use of coolants. Use the same practice previously employed. One factor should be observed, however. When using coolants, it is absolutely essential that a heavy, continuous flow be provided to prevent alternate heating and cooling of the tool.

(7) *Chucks, Clamps, and Holding Devices*—Chucks, clamps, and holding devices should hold the work solidly to prevent loosening during the machining operation.

This is particularly necessary at the higher speeds used with cemented carbide tools.

(8) *Grinding*—To obtain the greatest value from cemented carbide tool investment, tools should be reground before they become dull to the actual point of failure. By so doing, it is usually only necessary to remove a few thousandths from the tip to renew the cutting edge. Occasional stoning will also be found helpful in increasing the life of the tool. Special silicon carbide stones are available for this purpose. In addition, special diamond impregnated stones, or hones, as well as silicon carbide and diamond impregnated grinding wheels, are available. Diamond impregnated wheels are proving satisfactory for the resharpener and maintenance of cemented carbide tools. Proper maintenance of tools by users is essential to the successful use of cemented carbides.

(9) *Interrupted, or "Jump", Cuts*—Cemented carbide tools are being used with satisfactory results on interrupted cuts. However, lower speeds should be used than on continuous cutting. On severe jobs, the design of the tool should provide greater support for the tip than is ordinarily required.

Design Recommendations—Proper support is the most important requirement to be considered in the design of cemented carbide tools. Being hard, and usually not so strong as steel tools, the cemented carbide tip must have adequate support to perform efficiently. Based on this general requirement, the following conditions for rake angles and clearances should be provided:

- (a) Avoid all sharp angles which throw the stress upon an unsupported section of the cemented carbide tip rather than into the shank.
- (b) For clearance angles, provide only the absolute minimum necessary to clear the work.
- (c) For rake angles, the correct design is that which keeps all angles at a minimum consistent with the cutting qualities desired. Design of previous tools may be used as a guide in determining where angles are necessary, but the degree of angles should be kept to an absolute minimum. In general, it will be found that the angles used on previous tools may be substantially reduced without jeopardizing the cutting qualities of the cemented carbide tool.

The following recommendations may be used as a general guide in determining correct angles. Those recommended may, of course, vary according to the individual requirements of any given job, but the figures shown will give some indication of correct cemented carbide tool practice:

	Clearance	Side Rake	Back Rake
Aluminum	8°-12°	12°-16°	20°-40°
All other nonferrous.....	6°-12°	5°-15°	0°- 6°
Ferrous metals (except steel).....	4°- 6°	3°-10°	0°- 4°
Nonmetallics.....	8°-10°	5°-15°	3°- 6°
Steel	6°- 8°	10°-20°	4°-10°

(c) *Wear and Corrosion Resistant Applications*—The cemented carbides are being used where localized wear or corrosion is a problem. This classification includes small tools, as well as parts and accessories for production machines. Typical applications are as follows:

Lathe and grinder centers (male and female).
 Lathe work and follow rests.
 Centerless grinder work rest blades.
 Grinder fingers, profiles, and cams.
 Gages of all types, micrometers, indicator points.
 Colling guides, colling arbors.
 Guides, all kinds, for the wire, paper, textile, and shoe industry.
 Valve stems and seats for hydraulic presses and refrigerators.
 Ball valve and seats for oil well and other type pumps.

Meter fingers and pawls.
 Sandblast nozzles.
 Burnishing tools and dies.
 Chilling plates for the hardening and tempering of thin stock.
 Straightening and flattening dies or blocks.
 Mold liners for pharmaceutical, ceramic, and powdered metal arts.
 Grinder parts for the fine grinding of paint pigments, carbon products, and other abrasive materials.
 Brinell balls.

The cemented carbides are limited to the smaller applications of the above general type and should not be considered for such items as tank linings, gear teeth, or tractor treads.

An interesting application is the use of a cemented tungsten carbide grade as a contact material on relays and transmitters in telegraphic systems.

The fact that certain cemented carbides have compressive strengths higher than other known materials has been instrumental in furthering a new field of experimentation by which pressures of 50,000 kg./cm.² are being applied to solids, and the parameters of any transitions measured. This work is being conducted currently by P. W. Bridgman² at the Research Laboratory of Physics, Harvard University. The cemented carbide material is being used as the pistons for applying the high pressures used.

Fabrication of Dies, Tools and Wear Resistant Parts—The cemented carbides are applied to the above type applications as solid pieces, or generally as inserts brazed or mechanically attached to steel or other supporting members. The attaching and processing of the cemented carbides after final sintering is described below.

Dies and Mandrels—The nibs or inserts, as removed from the sintering furnace, are generally ground on all outside faces to given dimensions and to close tolerances. The small ground die nibs are press fitted into alloy steel, stainless steel, Monel or bronze cases.

The large ground die nibs are put in alloy steel casings while the casing is at an elevated temperature. On cooling, the steel case shrinks around the die nib and holds it securely.

This procedure is also used for holding cemented carbide die nibs which have been made in more than one piece. Shaped dies and exceptionally large round dies are generally fabricated in more than one piece.

Other methods in use for the holding of die nibs are: Casting of a case around the nib; forging of a case around the nib; and in some instances a brazing procedure is followed.

Cemented carbide tipped mandrels generally have the tip in the form of a cylinder. This cylinder is held mechanically by means of a closely fitted screw threaded into a heat treated shank.

After the cemented carbide nibs or inserts are mounted in the supporting case, they are finished to the form, size, and polish desired by the use of powdered abrasives. The powdered abrasives in general use are diamond, boron carbide, and silicon carbide, and their ability to remove stock is the order listed with the diamond occupying the pre-eminent position.

The diamond powder is obtained by crushing, or breaking up, small industrial diamonds known as bortz. This crushed product is graded into several grades of powder by floating the diamond particles in olive oil under definite controlled time schedules. Boron carbide and silicon carbide powders are generally graded by sieving.

Special drilling and polishing equipment, using above abrasives, as well as technique, has been developed and is in general use for the manufacture and recutting of cemented carbide dies.

Tools, Wear and Corrosion Resistant Parts—The same general technique is followed for tools and wear resistant parts, so both are included under the one heading.

Cemented carbide tools and wear resistant parts are generally made up with the cemented carbide as a tip or insert. The remainder of the tool is generally a steel shank or holder.

In some instances, the cemented carbide is used as a tool or part without a supporting integral unit. These parts, however, are generally clamped, or inserted, into steel holders of one kind or another.

Brazing is the method widely used for attaching the cemented carbide tip, or insert, to the steel shank or holder. The brazing media in general use are copper, tobins bronze, and silver solders with suitable fluxes for each.

Most production brazing is done in either an electric or gas furnace which is generally of the muffle type. Whether gas or electric, the furnace should have a nonoxidizing atmosphere.

Many users satisfactorily braze their own tools using oxy-acetylene or oxy-hydrogen torches.

The shanks are generally made from steels having a carbon content of from 0.40-0.60% and of the low alloy type. A wide variety of steels can be used with

average success, but to date it has been found that a silicon manganese steel of the *chisel steel* type has the best all around properties.

The final grinding is usually done on standard tool room equipment, using silicon carbide or diamond impregnated grinding wheels. When necessary, the tool edges can be lapped, either with a cast iron disc and diamond powder, or with a diamond impregnated lapping wheel.

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⁴Carboloy Co., Inc., Profitable Use of Carboloy Cemented Carbides (Supplement SC-35).

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Cutting Fluids for Machining*

Part I

Definition—Cutting fluids, frequently referred to as lubricants or coolants, consist of those liquids, solids, and gases which are applied to the material being cut and the tool to facilitate the cutting operation. Suggested lubricants for cutting and forming dies operations are discussed in Part II of this article.

In metal cutting, it is desirable to have high cutting speed, long tool life, low cutting temperature, low power consumption, the best surface finish, and freedom from corrosion. In different operations these factors vary in importance and usually some are obtained at the expense of others. For instance, in heavy roughing cuts, temperatures as affecting distortion and surface finish are of little consequence. In screw machine work, however, surface finish, dimensional accuracy as affecting interchangeability, and long tool life are of great importance. For each case, desired results are obtained by varying the tool material and shape; the cutting speed, feed, and depth of cut; the structure of the material cut; and the cutting fluid.

Purpose of Cutting Fluids—A cutting fluid is used for the following purposes: 1. To keep the tool cool and prevent it from being heated to a temperature at which the hardness and resistance to abrasion are reduced. 2. To keep the work cool, thus preventing it from being machined in a warped shape resulting in inaccurate final dimensions. 3. Possibly through lubrication to reduce the power consumption, wear on the tool, and the generation of heat. 4. To provide a good finish on the work. 5. To aid in providing a satisfactory chip formation. 6. To wash away the chips (this is particularly desirable in deep hole drilling, hacksawing, milling, and grinding). 7. To prevent corrosion of the work and machine. 8. To lubricate moving machine parts close to the cutting tool.

Classification of Cutting Fluids or Coolants—Cutting fluids and coolants may be divided into the following classes: 1. Air used as suction or blast. 2. Water, either plain or containing an alkali. 3. Emulsions of a soluble oil or paste. 4. Oils, such as mineral, fixed, compounded, and sulphurized.

Types of Cutting Fluids and Their Applications—Air as a suction is often used with internal and surface grinding and polishing operations or on grinding and boring operations on gray iron. Its main purpose is to remove the small chips or dust from the air, although some cooling is obtained.

Aqueous solutions, containing up to 1 or 2% by weight of an alkali, such as borax, sodium carbonate, or trisodium phosphate, have high cooling properties and have sufficient corrosion prevention properties for some jobs. They are inexpensive and are sometimes used for grinding, drilling, sawing, light milling, or turning operations.

Emulsions consist of an emulsifying soluble oil or paste emulsified with water in the ratio of 1 part oil to 10-100 parts of water, depending upon the type of product and the operation. This is low cost cutting fluid and is used for practically all types of cutting and grinding when machining all types of metals. The richer mixtures of oil and water, such as 1-10, are used for broaching, threading, and gear cutting, where an oil is not required to secure the desired surface finish or machine lubrication. For most operations a solution of 1 part soluble oil to 20 parts water will be satisfactory for turret lathe work, some screw machine work, gear hobbing, and drilling. Leaner mixtures may be used on simple turning or drilling operations. Lean mixtures, such as 1-50 or up to 100, may be used on some drilling and most grinding operations. In many instances the concentration of the emulsion is determined by the rust prevention requirements of the metal being machined or the lubrication requirements of the machine and not by the actual machining operation.

A variety of oils are used for metal cutting. They are used where lubrication rather than cooling is essential, or where a high grade finish is desirable, although sometimes superior finishes are obtained with the emulsions.

Sulphurized oils are used generally as cutting fluids for rapid production involving good surface finish and close tolerances on metals difficult to machine. These sulphurized oils may be classified into three groups as follows:

1. Sulphurized mineral oils—These cutting fluids contain up to 4% active sulphur in straight mineral oil.

*Prepared by the Subcommittee on Cutting Fluids. The membership of the subcommittee was as follows: O. W. Boston, General Chairman; Joseph Geschell, Chairman; M. N. Shepherd, H. L. Moir, C. B. Harding, G. F. Bowers, Floyd Fritts, A. C. Starling, W. D. Huffman, J. M. Jackson, C. L. Foreman, H. E. Martin, Raymond Haskell, W. H. Oldacre, E. M. Slaughter, Maurice Reswick, and M. W. Reynolds.

2. Sulphurized compounded oils—These oils are combinations of fatty oils, such as lard, rapeseed, degrass, sulphur, and petroleum oils.

3. Sulphurized base oils—These are concentrates containing relatively high percentages of sulphur compounds which the user blends with mineral oil to meet individual requirements.

Sulphurized oils are used extensively in broaching, gear cutting, automatic screw machine work involving threading and tapping on straight carbon or alloyed steels and hot rolled steels. They are satisfactory also for machining stainless steel, high nickel alloys, and copper.

In addition to the above, various chemicals such as phosphorus and chlorine compounds may be used in cutting fluids. Graphite, mica, white lead, and similar solids are sometimes used. (See Part II for further applications of cutting fluids for copper, aluminum, steel and zinc.

Quantity of Cutting Fluid—Best results are obtained when any of the cutting fluids are applied to the work and tool in ample quantities such as 3-5 gal. per min. for each single point tool.

Part II

Lubrication of Metals for Fabrication and Cutting

By B. H. McGar*

Aluminum—When drawing light gage aluminum, a petroleum oil having a viscosity of 100-200 seconds Saybolt at 100°F. will give satisfactory results, or a solution composed of 75% petroleum oil with a 200 viscosity and 25% lard oil with a maximum free fatty acid content of 3% may be used. On light gage difficult draws, a lubricant composed of 50% high viscosity petroleum oil and 50% lard oil having a total free fatty acid content of 3% is satisfactory. For heavy gage aluminum, use straight low free fatty acid oils.

For cutting ordinary aluminum, a solution composed of 50% kerosene, 40% lard oil with a low free fatty acid content, and 10% of a chlorinated solvent such as carbon tetrachloride or trichlorethylene is used. Attention should be called to the toxicity of these solvents and they should be used with caution. When using free machining aluminum, a compound composed of 75% low viscosity petroleum oil and 25% lard oil may be used, or 1 part of sulphur base oil compounded with 9 parts of light petroleum oil. (See also page 1315 the article on Machining Aluminum and Aluminum Alloys.)

The above lubricants may be removed from the articles in a modern vapor degreasing equipment. This may be followed by washing in a mild, properly inhibited alkaline cleaner at a temperature not to exceed 185°F., thorough rinsing in clean water, and drying.

Copper and Copper Alloys—As an aid in forming, stamping, and drawing strip brass or copper, a suitable lubricant must be used. For most operations, a 3% aqueous solution made from a good grade of soap chips will furnish an excellent lubricant. The solution should be kept slightly warm so as to prevent it from forming a gel. For more intricate operations, it is sometimes necessary to use a 3% water solution of a compound composed of approximately 30% water, 30% free fats, and 40% soap. Compounds of this general character are readily obtainable on the market.

Previous to the drawing operation, the strip brass or copper can be completely submerged in the lubricant and drained, or the solution can be applied with a swab or, better still, applied by felt rollers which pick up the lubricant and distribute it evenly over the surface of the strip as it is fed into the press. Partly formed or drawn articles are immersed in the solution and allowed to drain before again being placed in the press for redrawing.

Regardless of whether the article is to be left in the as-drawn condition or later annealed, it is good practice to wash the articles shortly after drawing to prevent red stains. The lubricant can be removed from the article in a suitable alkaline cleaner, which may be composed of a proper mixture of caustic soda, soda ash, trisodium phosphate, and sodium silicate, together with a wetting agent. Usually 3-5 oz. of cleaner are added to 1 gallon of water and used at approximately 185°F. The articles are then thoroughly rinsed in cold and hot waters and dried.

A satisfactory lubricant for cutting, drilling and tapping leaded or free cutting brasses is a light machine oil sometimes known to the trade as pale paraffin oil, having a viscosity of about 100 seconds Saybolt at 100°F. One part of sulphonated soluble oil to 10-20 parts of water may also be used. When it is necessary to machine nonleaded brasses, mixtures varying from 75-90% of machine oil and 10-25% of lard

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oil may be used. Copper is more difficult to machine than brass, but various satisfactory lubricants are used, such as 3 parts of this machine oil and 1 part of lard oil, or 1 part of highly sulphurized fatty oil, so-called sulphur-base or sulphonated oil and 10 parts of light machine oil. Also, a satisfactory lubricant can be made by adding materials such as tricresylphosphate to machine oil to improve the film strength. (See also the article on Machining Copper Alloys.) These lubricants may be removed in a vapor degreasing equipment using trichlorethylene, or in alkaline cleaner solutions made by using 3-5 oz. of the cleaner per gal. of water, and maintaining the bath at about 185°F. After the cleaning operation, the articles should be thoroughly rinsed and dried.

Magnesium—See the article on Machining Magnesium and its Alloys.

Nickel—See the article on Machining High Nickel Alloys for the lubricants used.

Steel—When drawing, forming or stamping soft light gage steel sheet or strip, a suitable lubricant can be compounded by adding $\frac{1}{4}$ lb. of deodorized fish oil soap to 1 gal. of water, or by using light petroleum oil that has a viscosity of 100-200 seconds Saybolt at 100°F. Satisfactory results may also be obtained by applying a heavy emulsion composed of 1 part naphthenic base soap to 4-5 parts of water.

When a deep or intricate draw is required, a solution made of 1 part of drawing compound consisting of 20-25% soap, 40-45% free fats, 35% moisture and 3 parts of water will be found satisfactory. Some operators prefer to use a solution composed of 5 parts of water and 1 part of filled drawing compound, the latter being composed approximately as follows: 15% soap; 20% filler (such as tale, fine clay, calcium carbonate, barium sulphate); 30% free fats; and 35% water.

For light drawing of medium gage sheet steel, 1 part of filled drawing compound in 2 parts of water is suitable. Also, a solution made by adding $\frac{1}{4}$ lb. of deodorized fish oil soap to 1 gal. of water may be used. When deep drawing the heavier gages, it is common practice to use filled compounds composed of 40-60% filler and 40-60% free fats without dilution. It is also possible to use straight sulphur-base oils for such operations. When selecting a lubricant for the above operations, some care and thought should be given to the subsequent operations and what type of finish will be ultimately applied to the article, as the cleaning problem may present difficulties.

High carbon and alloy steels may be cut, threaded, or milled, using various types of lubricating compounds. When heat transfer and chip removal are of primary importance the work should be flooded with a solution made by adding 1 part of soluble cutting oil to 9 parts of water. The soluble cutting oil may be composed of 15-20% naphthenic base soap and 80-85% petroleum oil of 200-500 viscosity. Various proprietary compounded oils of the chlorinated type may be also effectively used. If a smooth finish and long tool life are required, 1 part of sulphur-base oil and 9 parts of light petroleum oil may be used. A mixture of lard oil and turpentine in varying proportions is used for machining hard steel and for drilling.

When cutting and machining low carbon steel, 1 part of soluble cutting oil base and 19 parts of water is satisfactory, or 1 part of sulphur-base oil with 15-20 parts of light petroleum oil may be used. Likewise, a lubricant composed of approximately 90% mineral oil, viscosity 250 seconds Saybolt at 100°F., and 10% lard oil, maximum free fatty acid content of 3.5%, will be found satisfactory. Sometimes free fatty acid (1-5% oleic acid) is used as compounding.

The sulphur-base oil and petroleum oil can be removed from the articles by using a modern vapor degreaser. This operation is sometimes followed by cleaning the articles in a good grade of alkaline cleaner. Frequently articles that are machined with soluble oils as a lubricant are not cleaned, as the film of oil remaining acts as a rust preventative.

Zinc—Zinc may be successfully drawn in a 3-5% aqueous chip soap solution; sometimes it has been found beneficial to add to this solution a small portion of lard oil. The lubricant may be applied to the sheet zinc in any of the ways mentioned under copper and brass.

When it is necessary to machine, cut or thread zinc, a solution composed of 1 part of neutral sulphonated soluble oil base and 14 parts of water has been found satisfactory. The drawing and cutting solutions can be cleaned from the zinc articles by washing in a mild, properly inhibited alkaline cleaner made up by adding 3-4 oz. of cleaner to 1 gal. of water and maintaining the temperature at approximately 180°F. After the washing operation the articles should be thoroughly rinsed in hot and cold waters and then dried.

Cutting of Metals*

(Gas and Electric Arc)

Cutting of Metals—Gas—Gas cutting of ferrous metals is a process of preheating the material to be cut to its kindling or ignition temperature and then rapidly oxidizing it by means of a closely regulated jet or stream of oxygen issuing from a special tool called a cutting blowpipe or torch. Hence, the process is primarily a chemical one, based on the remarkable chemical affinity of oxygen for ferrous metals, when raised to or above the kindling temperature.

The chemical reaction which results when commercially pure oxygen is brought into contact with most steels or iron, at kindling point, is an active one. In the case of carbon steel, the metal is preheated to a bright red color, in daylight, reached approximately between 1400 and 1600°F. The gases supplied and the rate of progression of the cutting should be closely regulated for accurate control.

Only the metal within the direct path of the oxygen jet is acted upon. In linear cutting, or severing, a narrow race or kerf, as it is usually called, is formed, having uniformly smooth and parallel walls. Under skilled workmanship, using mechanically guided cutting torches or blowpipes, cutting tolerances as to squareness and longitudinal alignment of the cut surface may be held within close limits.

The faces or walls of the kerf, in the commonly used carbon steels, are not injured by the cutting operation. On the contrary, their strength and toughness are slightly improved. The heat effect upon the metal resulting from normal cutting operations rarely penetrates more than approximately 0.1 in. below the cut surface in any case.

In addition to the chemical reaction in cutting, there is a noticeable and helpful mechanical eroding effect produced by the kinetic energy or motive power of the cutting oxygen stream. This washes away considerable of the molten metal in unconsumed or metallic form and adds to the efficiency and economy of the process.

With this process, heavy cuts can be made with practically the same economy as cuts made in the lighter gages. Heavy sections, heretofore uneconomical to cut by any of the mechanical cutting processes are readily and smoothly cut with oxygen.

In addition to linear gas cutting or severing, several other types of controlled oxidation are in use, which employ the free burning reaction of oxygen with ferrous metals raised to kindling temperature, to provide further facilities for severing, shaping, and working with such materials. One application, known generally as "oxygen lance cutting", utilizes a relatively long section of small diameter iron pipe. The end of the pipe is ignited and kept so by a stream of oxygen flowing through the pipe. This furnishes preheat as well as free oxygen for cutting, thus forming a lance-like cutting tool which is used primarily for emergency and heavy duty cutting, such as opening up furnace tap holes.

Another application of gas cutting is known as "flame machining". This method is used primarily to surface ferrous metals in much the same way as a planer or milling machine. The cut does not penetrate through the work, as in severing or linear gas cutting.

Chemistry of Gas Cutting—Oxidation of Ferrous Metals—The oxide of iron formed in gas cutting is a black, brittle substance, identical in composition with hammer scale or magnetite ore. Its chemical formula is Fe_3O_4 . This latter substance contains a smaller proportion of oxygen than rust or red iron oxide, Fe_2O_3 . As indicated in Fig. 1, the completed equation for the oxidation reaction in gas cutting is:



Three atoms of iron (Fe) combine with two molecules of oxygen (O_2) to produce one molecule of magnetite (Fe_3O_4). In this oxidation reaction, 1593 calories per gram or 2870 B.t.u. per lb. of iron are produced, which represent the calorific energy of the iron. As the atomic weight of iron (Fe) is 55.84 and the molecular

*This article was prepared under the sponsorship of the International Acetylene Association, who appointed a special committee to handle the work. The International Acetylene Association felt that in order to do full justice to the subject, they should invite electric welding experts and users to join their committee. The full membership of the committee was as follows: C. W. Obert, Chairman, The Linde Air Products Co.; E. V. David, Air Reduction Sales Co.; L. D. Meeker, General Electric Co.; E. W. P. Smith, Lincoln Electric Co.; A. G. Wilkoff, Union Carbide Company; C. H. Jennings, Westinghouse Electric & Mfg. Co.; H. L. Maxwell, E. I. du Pont de Nemours & Co., Inc.; and W. L. Warner, Watertown Arsenal.

weight of oxygen (O_2) is 32, it follows that the relative weights of the iron and the oxygen in magnetite (Fe_3O_4) are as 167.52 is to 64.00, or as 2.618 is to 1. Or, expressed otherwise, 1 lb. of oxygen will oxidize or consume 2.618 lb. of pure iron. Oxygen, at 70°F. and 1 atmosphere pressure, has a volume of 12.07 cu.ft. per lb. and pure iron weighs 0.285 lb. per cu.in. Based on these constants, the following data may be computed:

- 1 lb. oxygen will oxidize 2.618 lb. or 9.186 cu.in. of pure iron.
- 1 cu.ft. oxygen will oxidize 0.217 lb. or 0.761 cu.in. of pure iron.
- 1 lb. of pure iron requires for oxidation 0.382 lb. or 4.610 cu.ft. of oxygen.
- 1 cu.in. of pure iron requires for oxidation 0.109 lb. or 1.314 cu.ft. of oxygen.

In actual gas cutting, the iron or steel removed from the kerf is, as already noted, not entirely oxidized or consumed by the oxygen, but, due to the eroding effect of the cutting oxygen jet, about 30-40% of the metal is washed out of the cut, as unconsumed or metallic iron. Owing to this fortunate circumstance, it is not uncommon to obtain satisfactory cuts with a cutting oxygen consumption of even somewhat less than one cu.ft. of oxygen per cu.in. of material removed from the kerf. This, as may be seen from the above data, is more than 30% better than the theoretical figure, based on chemical reaction alone.

Carbon steels contain such elements as carbon, manganese, and silicon in combined form but in proportions that have little or no influence on the oxidation of the metal in gas cutting. These are oxidized or dissolved in the slag without interfering with the progress of the cut. However, certain alloy steels contain chromium, nickel, and other elements in sufficient amounts to have a marked retarding effect on the oxidation reaction. The uncombined or graphitic carbon in cast iron has a similar influence. Such materials are harder to cut with gas and require special technique.

Combustion of Fuel Gases—A number of higher flame temperature fuel gases have been employed for cutting ferrous metals, with varying degrees of success. The more important of these are: Acetylene, hydrogen, city gas, natural gases, coke oven gas, ethylene, and the lighter petroleum distillates, including methane, ethane, propane, and butane. Table I gives combustion constants for certain of these fuel gases.

Table I
Combustion Constants of Fuel Gases

Name of Gas	Chemical Equation for Complete Combustion	Heat Value B.t.u. per cu.ft.	Flame Temp. With Oxygen, °F.
Acetylene.....	$C_2H_2 + 2\frac{1}{2}O_2 = 2CO_2 + H_2O$	1433 net	6300
Hydrogen.....	$H_2 + \frac{1}{2}O_2 = H_2O$	275.1 net	5400
City gas.....	Typical mixture	300-800 net	4600
Natural gas.....	Typical mixture	800-1200 net	4600
Coke oven gas.....	Typical mixture	500-550 net	4600
Methane.....	$CH_4 + 2O_2 = CO_2 + 2H_2O$	913.8 net	5000
Ethane.....	$C_2H_6 + 3\frac{1}{2}O_2 = 2CO_2 + 3H_2O$	1631 net	5100
Propane.....	$C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$	2309 net	5300
Butane.....	$C_4H_{10} + 6\frac{1}{2}O_2 = 4CO_2 + 5H_2O$	2999 net	5300
Ethylene.....	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$	1530 net	5100

Aside from hydrogen all of these fuel gases are hydrocarbons and, as shown in Table I, give off carbon dioxide (CO_2) and water vapor (H_2O) as products of complete combustion. They may be burned in different manners, but, when used for gas cutting, the combustion is made to take place in the way that will develop maximum flame temperatures. For quick starting and rapid progress of a cut hot preheating flames are a prime essential. This condition is fulfilled by designing cutting torches or blowpipes to burn the fuel gases on the Bunsen principle and to premix commercially pure oxygen instead of air with them before combustion. The substitution of oxygen in place of air for the primary combustion results in a notable increase of flame temperature of the fuel gas, as the nitrogen, constituting nearly four fifths of the air, must not be heated by the flame when oxygen is used. In the case of acetylene, a hot and short flame, with an easily distinguished, bright inner cone is produced, the hottest point being at the inner cone tip. Hydrocarbon gas flame structures are of a complex nature, with a multiplicity of cones, caused by the successive chemical reactions taking place in different stages.

Depending on the ratio of oxygen to fuel gas in the mixture, the characteristic of the flame produced may be carburizing, neutral, or oxidizing. The neutral flame results when just sufficient oxygen is supplied to complete the primary combustion in the inner flame cone, giving carbon monoxide (CO) and hydrogen (H₂) as products. Neither of these two gases has any tendency to carburize or oxidize molten metal, but are neutral to it. Regardless of the amount of primary oxygen supplied, complete combustion in the inner flame cone is impossible since, at such extremely high temperatures, carbon dioxide and water vapor are unstable and dissociate or revert back in part to carbon monoxide, hydrogen and oxygen. This dissociation limits maximum attainable oxy-fuel gas flame temperatures, which otherwise might go much higher.

Maximum flame temperatures are obtained with strongly oxidizing flames, which type, therefore, are generally used for gas cutting. Oxidizing flames preserve the general appearance of neutral flames, but their inner cone is shorter, "necked in" on the sides and not so sharply defined. Due to dissociation, the products of the primary combustion in the inner cone of excess oxygen flames consist of carbon monoxide, carbon dioxide, hydrogen, water vapor, and free oxygen, in proportions depending upon the amount of excess oxygen premixed with the fuel gas.

The secondary combustion of the fuel gas takes place in the outer or envelope flame. Here, any carbon monoxide or hydrogen contained in the primary combustion products complete their combustion to carbon dioxide and water vapor, respectively, as the lower temperature is insufficient to cause dissociation of these latter compounds. The necessary oxygen required for completing the secondary combustion in the envelope flame is taken from the surrounding air by diffusion into the zone.

Table II gives optimum gas ratios and equivalent volumes of oxygen and acetylene, city gas, natural gas, and propane required for gas cutting the same work at the same speed.

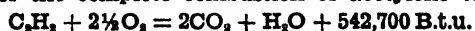
Table II
Equivalent Fuel Gas and Preheating Oxygen Volumes for Cutting

Name of Fuel Gas	Optimum Ratio Oxygen to Fuel Gas	Gas Consumption Preheating Oxygen	Cu.ft. per hr. Fuel Gas
Acetylene	1.7 -1	17	10
City gas	0.75-1	56	75
Natural gas	2.0 -1	56	28
Propane	4.5 -1	54	12

The data in Table II applies only when each fuel gas is utilized at its maximum efficiency. In practice it is difficult for the operator to adjust the gas ratio of other gases than acetylene to even approximately correct values. Because there is no definite starting point, such as the neutral flame in the case of acetylene, even an experienced operator frequently adjusts the gas ratio of the flames utilizing other fuel gases to much higher gas ratios than the best values indicated by Table II. Obviously this involves the use of much more oxygen than otherwise would be required. With acetylene, the change in the size and brilliance of the flame when adjusted to the oxidizing side of the neutral flame is great enough to make it quite unlikely that any operator will employ appreciably higher oxygen-acetylene ratios than necessary.

Furthermore, when certain other fuel gases are used, the oxygen requirements for the cutting jet are also greater than when acetylene is used. This is particularly true where the preheating gas consumptions are large and the resulting gases of combustion are sufficient to pollute the cutting oxygen jet. In such cases a noticeable deterioration in the cutting efficiency may ensue.

Combustion of Acetylene—As acetylene is the most widely used fuel gas for cutting, its combustion will be described in greater detail. Table I and III show the chemical equation for the complete combustion of acetylene to be:



In other words, 1 molecular volume of acetylene unites with 2½ molecular volumes of oxygen to form 2 molecular volumes of carbon dioxide and 1 molecular volume of water vapor, with a liberation of 542,700 B.t.u. of heat.

Most hydrocarbons are exothermic, generating heat during formation and absorb-

ing the same amount of heat during combustion. But acetylene is highly endothermic, absorbing heat during formation and liberating it again on burning or decomposing. The endothermic heat liberated by acetylene is in addition to that produced by the combustion of its component elements. The total heat generated is given in Table III.

Table III
Heat Produced by Complete Combustion of Acetylene

	Reaction Formula	B.t.u. Per Molecule	B.t.u. per Cu. Ft. at 60°F. and 1 Atmos.	% of Total
Endothermic	$C_2H_2 = 2C + H_2$	86,600	228	15.9
Carbon	$2C + 2O_2 = 2CO_2$	352,000	928	64.8
Hydrogen	$H_2 + \frac{1}{2}O_2 = H_2O$	104,100	277	19.3
Total heat of combustion.....		542,700	1,433	100.0

Acetylene contains the highest percentage of carbon (92.3% by weight) of any common gaseous hydrocarbon compound. This, coupled with its exceptionally large endothermic heat, gives it the highest flame temperature by a wide margin of any known fuel gas.

Oxygen Purity—High purity oxygen is essential for rapid and efficient cutting. Even a small percentage of impurities in oxygen causes a great loss in its cutting quality. Tests of machine cutting 12 in. mild steel billet in the laboratory, under identical conditions, using oxygen from 97.5-99.5% pure, gave results summarized in Table IV. The results demonstrate clearly the importance of high purity oxygen for cutting.

Table IV
Effect of Oxygen Purity on Consumption

Purity, %	Oxygen Consumption	
	Cu.ft. per Linear Foot Cut	Increase, %
99.5	45.5	....
99.0	49.5	8.8
98.5	55	20.9
98.0	63	38.5
97.5	73	60.5

Effect of Gas Cutting on Steels—In gas cutting, a slight depth of metal immediately adjacent to the cut face is raised to a bright red heat or considerably above the critical range. As the cut progresses, the steel cools again through this range. The speed of cooling is dependent upon the heat conductivity of the surrounding metal, radiation losses, and the fact that the heat is applied only momentarily at any given point, the cutting torch being kept in constant motion while cutting. Where the steel being cut is at room temperature, the rapidity of the cooling is sufficient to actually have a chilling or quenching effect on the cut edges, particularly in the case of heavier cuts involving large masses of cold metal.

When polished and etched specimens are taken from gas cut edges and examined under the microscope, the material is found to be altered when compared with the original metal. However, the change is largely a physical one, concerned with crystalline grain structure. The normal pearlitic steel is transformed into one or more of several structures ranging from spheroidized carbides in the ferrite to the harder constituents, depending upon the particular chemical composition of the steel cut and the rate of cooling following the cutting operation, as well as the carbon content and the alloying elements present. Also, an alteration in grain dimension at the gas cut edge is induced due to the intensity of the heat developed by the cutting to render the grains either larger or smaller than the unaffected grain behind the cut edge.

Low Carbon and Mild Carbon Steels—Gas cutting of carbon steels at normal temperatures containing less than 0.35% carbon is not detrimental. Indeed, gas cut edges of such steels are suitable for any uses where edges prepared by any of the mechanical methods of severing, as for example planing, milling, shearing, friction sawing and grinding, are employed. Gas cut edges are adapted to applications involving stresses, such as mechanical calking and holes in which tubes are to be

expanded or rivets driven. Clean, smooth gas cut edges of low or medium carbon steel plates or forgings actually have physical properties that render them superior to sheared, planed, or otherwise mechanically prepared edges.

An investigation of the conditions which develop when the fusion welding process is applied to gas cut edges, conducted a few years ago by the A.S.M.E. Boiler Code Committee, produced such conclusive results that all restrictions in the Boiler Code pertaining to welding on gas cut surfaces were removed. The wording of the Code requirement, which was adopted in 1935 for incorporation in the Power Boiler and Unfired Pressure Vessel Sections, is as follows:

"Preparation for Welding—The plates may be cut to size and shape by machining or shearing, or by flame cutting if the carbon content does not exceed 0.35%. If shaped by flame cutting, the edges must be uniform and smooth and must be freed of all loose scale and slag accumulations before welding. The discoloration which may remain on the flame-cut surface is not considered to be detrimental oxidation."

Where edges are gas beveled to form a vee for welding, and later are welded together, either by oxy-acetylene blowpipe or electric arc, the heat of the welding operation acts to dissolve all previously formed marginal structures and operates to anneal the metal for an appreciable depth below the cut surface. Any change in structure that the preceding cutting may have produced in and adjacent to the cut surface is therefore obliterated.

Tests of flame cut edges of low and medium carbon steels to determine their physical properties, such as hardness, microstructure, resistance to impact, and ductility have shown that they are satisfactory for almost any type or character of mechanical treatment or service.

Higher Carbon and Alloy Steels—Gas cutting of higher carbon and alloy steels, particularly at room temperature, may produce a thin layer of hard material on the cut surfaces which may not be sufficiently ductile to withstand the stresses set up in cooling without cracking, or imposed by the subsequent use of the part cut. As the steel is momentarily highly heated by the torch at the cut edges it tries to expand but is restrained by the adjoining cold metal. The action called "upsetting" results. Later, when cooling occurs, contraction of the upset metal may develop severe stresses in tension along the cut edges. With these steels, the ductility may

not be sufficient to prevent incipient cracks and checks which can prove dangerous in service, as they are apt to develop into large fractures.

Preheating and Annealing—Experience has shown that if these higher carbon and alloy steels are preheated and in certain cases annealed after ward, no cracks will occur on the cut edges. Naturally, with the adjoining metal preheated, the difference in expansion between it and the metal heated during cutting is less and "upsetting" is greatly reduced or eliminated.

Certain steels may be preheated to as high as 1000°F. or more for gas cutting. However, care must be exercised not to carry the preheating too far, as the metal may develop too great an affinity for the cutting oxygen jet at elevated temperatures, thus

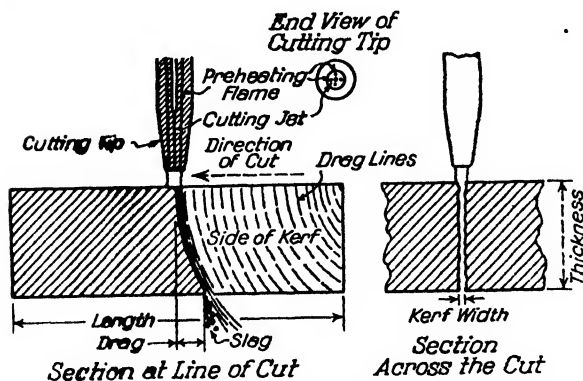
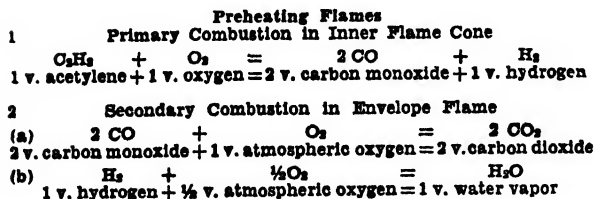


Fig. 1—Chemistry of oxy-acetylene cutting.



causing it to act erratically and prevent proper control of the cut. Special precautions should be taken in cutting particularly thick preheated sections to see that the work is done as quickly as possible after the piece has been withdrawn from the

furnace. This avoids having the interior considerably hotter than the metal at the surface, which condition may arise if the piece is allowed to partially cool in air before cutting. In the latter case, the oxygen jet may start its penetration without much difficulty, but upon entering the interior of the section fail to go through and cause a flare-up in the cutting. This stoppage is due to the hot center, which oxidizes so readily that a cavity or pocket may form on the inside of the piece. Where this occurs, a slight lowering of the cutting oxygen pressure often will be found to clear up the trouble.

To obtain the most efficient use of the oxygen and, at the same time, leave the steel in the best condition, a preheat temperature of 500-600°F. ordinarily should suffice for carbon steels. The additional expense that accompanies preheating is compensated for by the more rapid rate at which preheated steel can be cut.

Annealing completely restores the original pearlitic structure of the steel at the cut edges, wherever this may be desired, and removes any internal stresses set up in the metal. If carried out, it should be done immediately after cutting. Annealing temperatures suitable to the type of steel in the piece are employed. These temperatures are ordinarily in the neighborhood of 1250-1450°F. Annealing time depends on the grade of the steel, its thickness and shape.

When preheating has been used before flame cutting, the majority of steels do not require annealing. This applies to the steels which harden only when rapidly quenched from temperatures above the critical point. However, the air hardening steels must be annealed or cooled very slowly after cutting, if preheated. The low alloy, high strength steels of nickel, silicon, and manganese grades usually are in this category. For these it is essential that the postheating does not exceed the critical point.

Flame Softening—Flame softening is a localized and progressively applied oxy-acetylene heat treatment, similar in its physical aspects to flame hardening, but directly opposed in its objective. The results of flame softening are similar to those obtained by preheating in a furnace, but the effect can be restricted to a small area and the process is comparatively simple and economical.

Flame softening can be applied in any one of several ways. In some cases it is of advantage to preheat the metal locally prior to cutting; in others the heat treatment is applied after cutting, either directly to the cut surface or to the metal adjacent to the cut. The most effective and economical method to employ depends upon the dimensions and composition of the metal to be treated, as well as upon such factors as the service for which the metal is intended and the results sought.

Mechanical Effects of Gas Cutting—Properly performed gas cutting on carbon and low alloy steels produces accurate results. Top and bottom edges of cut are sharp and width of kerf uniform. Surfaces of cut may be smooth and square and be produced without "drag" lines. Precision obtainable depends upon: (1) The cutting equipment and procedure employed. (2) The cutability of the material. Other mechanical effects of gas cutting result from warping, due to the expansion and contraction of the steel in heating and cooling. When a part is locally heated, as in gas cutting, it may warp, unless: (a) Its stiffness or cross sectional strength is sufficient to resist the forces set up. (b) It is held in place by clamps or weights while cutting and cooling. (c) It is multiple cut simultaneously or in rapid succession about its neutral axis, thus equalizing the forces set up and neutralizing their effect. (d) The cutting operation is immediately and progressively followed by rapid cooling or quenching with a suitable medium.

Plates of $\frac{1}{2}$ in. thickness and above are seldom warped or buckled by gas cutting, unless unduly long and narrow. In such simple operations as cutting off rods, bars, rails, piping, structural shapes, and similar lengthy materials, warpage is not involved. So-called "skip-cutting" is frequently used in splitting narrow materials, such as flat bar stock and structural I-beams and channels to prevent warpage. In this method, the cut is made to skip at intervals, depending on the work, leaving a series of uncut sections along the line of cut, each about $\frac{1}{2}$ in. to 1 in. long. These uncut ligaments hold the material in line until cooled, whereupon they are cut through to separate the parts. Sometimes simultaneous cuts, made with two or more torches, moved together along parallel lines, are used to eliminate warpage, increase production and reduce costs. For some operations, such as beam splitting, water quenching is an effective check to warpage. Where great accuracy is demanded in over-all dimensions of larger cut parts, suitable correction factors must be applied in making the cutting layout, particularly where the steel is preheated.

Gas Cutting Equipment—Gas cutting equipment consists ordinarily of the cutting torch or blowpipe with separate cutting tips of different sizes, oxygen and fuel

gas hose with connections, oxygen and fuel gas pressure regulators, and gas cylinders. The pressure regulators usually are equipped with cylinder and working pressure gages. Cutting oxygen regulators are designed especially to deliver oxygen in large volumes and at higher pressures and, hence, usually are fitted with 400 psi. working pressure gages.

Where larger quantities of oxygen are required, oxygen cylinders often are manifolded. Acetylene generators, rather than cylinders, are used where the consumption justifies it. For such installations, distribution pipe lines frequently are employed to carry both gases to the various points of consumption throughout the

premises. For machine gas cutting, the torch is held and operated mechanically, but its essential features and the accessory equipment remain unchanged. To assure safety and efficient results, the manufacturer's instructions for setting up and operating the equipment should be followed closely in each case.

Gas Cutting Processes—Flame Cutting—The primary use for gas cutting is that of severing. With this process, the cut is made through the material as at (a), Fig. 2, leaving the cut edges in a plane usually at 90° to the surface of the part cut. The cutting tip preferably is held perpendicular to the surface, as shown, although in certain cases it may be tilted somewhat along the line of cut. For bevel cutting, the tip is tilted to the required angle or a bent tip is used, but the cut still penetrates through the material. These processes are widely known as "Flame Cutting."

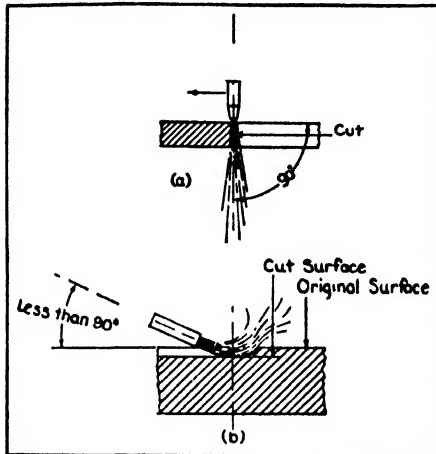


Fig. 2—Flame cutting.

Flame Machining—This process utilizes the same fundamental principle of chemical reaction, but the cutting oxygen stream is made to impinge on the work at a more or less acute angle, as at (b), Fig. 2; in some cases almost tangentially. The cut is not permitted to penetrate through the work, as in severing, but is restricted to removal of a predetermined depth and width of material from the surface by oxidation, as indicated. The various gas cutting processes are classified in Fig. 3.

Fundamental Principles of Flame Cutting—Drag and Quality—In flame cutting, the cutting oxygen jet usually enters the cut in line with the cutting oxygen orifice axis (a) in Fig. 2. After traversing about one-half the thickness of the cut, however, it may curve backward in a direction opposite to the travel (Fig. 1). When this occurs, the amount by which the oxygen jet falls behind the perpendicular in passing through the material is known as the "drag" of the cut. Faint markings or ridges called "drag lines" left on the face of the cut enable this to be measured, as shown in Fig. 1. In heavy cuts, these drag lines are more pronounced. Cuts with short or negligible drags are known as "high quality" cuts, while those with long drags are termed "low quality" cuts.

Cutting studies have shown that: 1. As the drag is decreased the oxygen consumption is increased. For very short drags, a slight decrease in drag length can be procured at the expense of increased oxygen consumption. 2. Except for low cutting speeds, a certain minimum length of drag is characteristic of a given tip and speed regardless of the operating pressure (or the oxygen consumption). 3. An increased drag may result if an attempt is made to obtain a drag shorter than the minimum by increasing the operating pressure beyond that at which the minimum drag is obtained.

In considering the economies of flame cutting, therefore, it is essential to determine how short the drag must be to fulfill the requirements. If it is too long, an uncut final corner will result and this is usually not permissible. Straight line cuts frequently may be made with considerable drag, without much detrimental effect, as the drag lines lie within the plane of the cut and do not prevent both top and bottom edges of the cut from being left clean and sharp. This procedure saves considerable oxygen. It is also applied in scrap cutting where cut quality is

nonessential, so long as severing is accomplished. However, in shape cutting, when rounding curves or corners, less drag is permissible, as the bottom contour of the cut will tend to come out differently from the top, with the edges not square. Such cuts must be made of small drag, high quality type. They require a good deal more oxygen than cuts with long drags which barely penetrate the material. Precision machine flame cuts are necessarily of high quality.

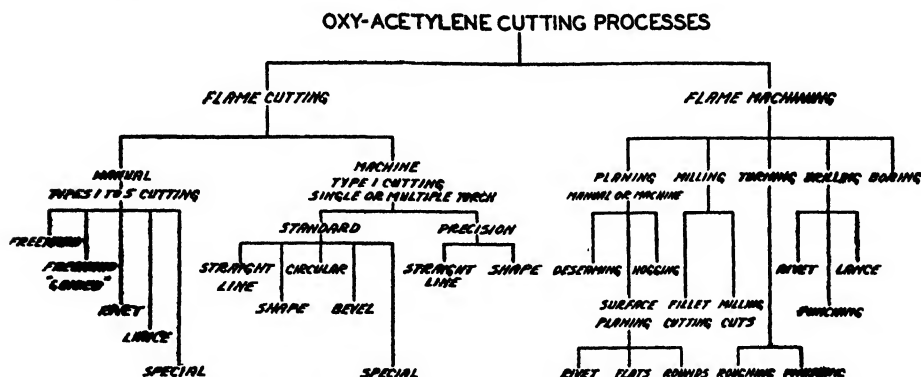


Fig. 3—Classification of gas cutting processes.

Satisfactory Commercial Flame Cuts—These must fulfill the following requirements: A. A sufficiently short drag; that is, the line markings on the face of the cut should approach the straight up-and-down condition. Drag should not be long enough to prevent the final corner being cut and the piece from dropping. B. The sides of the cut should be sufficiently smooth—not grooved, fluted or ragged. C. There should be no firmly adhering slag on the bottom of the cut, as this requires an appreciable expenditure of labor for its removal. With proper adjustments, only loose slag or none at all is obtained. D. The upper and lower edges of the cut should be sufficiently sharp to meet the requirements of the particular job. E. The cost must be moderate.

The following conditions are necessary to obtain smooth cuts: 1. Suitable cutting tip, with correct size cutting orifice and proper degree of preheat. 2. Proper oxygen and fuel gas pressures. 3. Correct cutting speed. 4. Uniformity of torch movement. 5. Uniform oxygen and fuel gas pressure regulation. 6. Smooth and uniform bore and proper type of cutting orifice. 7. Cleanliness of orifice exit. 8. Cleanliness of preheat holes. End of tip must be kept free from adhering slag. 9. High purity oxygen. 10. Proper angle of incidence of the cutting oxygen stream to the upper edge.

Selection of Cutting Tip or Nozzle—A wide variety of cutting tips or nozzles of different styles and sizes is available for flame cutting. They provide for cutting various thicknesses of most ferrous materials, and for different surface conditions, such as clean, painted, rusty, or scaly surfaces, as well as for a variety of special types of work. The thickness of the material to be cut governs the diameter of cutting orifice of the tip to be selected. The condition of the surface and composition of the metal determine the intensity of preheat flames which should be used. Rusty or scaly surfaces often are cleaned or "descaled" along the line of cut before cutting, by cracking the scale loose either with the torch preheating flames, or mechanically with scrapers or chipping hammers.

Starting Flame Cuts—In most cases, flame cuts are started at the edge of the piece. The cutting torch is held so that the ends of the preheating flame inner cones just clear the surface of the material. When a spot of metal at the top of the edge has been heated to a bright red, the cutting oxygen jet is turned on. The metal in the immediate path of the cutting jet oxidizes and, as the torch is moved slowly and steadily along the line to be cut, separation is effected. In flame cutting ordinary steel, the tip should be held vertically at a correct distance above the surface and advanced uniformly at the proper speed, without wavering.

Piercing Holes—In starting a flame cut in the metal away from the edge, or in piercing a hole, more time usually is consumed in bringing the spot to the kindling temperature, than with edge starting. When a spot has been heated to a bright

red, the torch is raised about $\frac{1}{4}$ in. above the normal position for line cutting and the cutting oxygen turned on slowly. As soon as the work is perforated, the torch is lowered again to the normal height above the surface and any further cutting that may be required is carried on. Drilled holes are used for certain work, particularly to form a straight, smooth starting edge for a heavy internal cut.

Cutting Rounds—When cutting round bar steel, gas pressures are set for the maximum thickness, or diameter, and the cut is started at the side. As the cut progresses, the torch is raised to follow the circumference. Starting is facilitated by nicking the round with a chisel to create a burr at the point where the cut is to begin, for the oxygen to take hold more easily.

Heavy Cutting—In heavy cutting, the greatest care must be exercised in selecting the proper operating pressure. Not only is the range of suitable pressures considerably narrower for the heavier cuts, but the pressure drops through the hose line connections and the torch becomes rapidly larger with the increasingly greater oxygen flows demanded for heavy cutting. Variations in the quality of the steel are also more important in the case of heavy cutting.

Considerable skill must sometimes be exercised in starting a heavy cut to completely sever the initial lower corner and avoid pocketing of the cutting oxygen stream in the lower portion of the cut. It is essential that the front edge of cut be very clean, particularly the lower portion of the front face. The axis of the tip should be aligned with the front edge of the material by turning on the cutting oxygen stream with preheating flames burning to render it visible. In starting the cut the movement of the torch should be retarded just long enough to allow the cutting stream to actively attack the material throughout almost its entire depth. Then the torch is permitted to proceed normally. If the piece is very heavy, the lower portion of the front face is sometimes heated with a large welding flame. In certain cases, starting is facilitated by first undercutting the forward edge of the material with a hand cutting torch, Fig. 4. Unless done by an experienced operator, however, poor and ragged cuts may be obtained by this method.

Care is also often required in completing the final corner of heavy cuts. A slight retardation of the forward movement of the torch is desirable here as well, but this must be properly carried out.

Scope of Flame Cutting—Thickness—With standard cutting torches not assisted by oxygen lances, present limits of penetration are about 24 in. for manual cuts and 33 in. for machine cuts. But thicker sections have been cut by making a non-penetrating cut in one side and then turning the piece over and making a second cut to join the first. Particularly for free hand flame cutting, the upper limit depends largely upon the skill and steadiness of the operator. With oxygen lances it is possible to penetrate through practically any thickness of metal.

Materials—Almost any ferrous material can be gas cut. However, certain steels contain sufficient alloying elements to offer considerable resistance to the process. The uncombined carbon in cast iron has a similar effect. For such materials, special flame cutting techniques, as described later, must be applied. Oxygen lances permit penetration of practically any material, ferrous or otherwise.

Cross Cut Tolerances—Where the torch is held firmly and advanced at uniform speed, as in machine flame cutting, cross cut tolerances can be kept within narrow limits. In ordinary steel of 6 in. thickness, cut surfaces can be held true as to cross sectional squareness to within $\frac{1}{16}$ in. Cuts in thinner sections can be held within proportionately smaller limits. The degree of longitudinal precision of a machine cut depends on the trueness of the guide rails of the cutting machine, the clearance of the operating mechanism and the regularity of the propelling unit. Machine cuts can be made so smooth and square and have such sharp edges that they require no further finishing of any kind.

Bevels—Angular or bevel flame cuts are accomplished by inclining the torch and tip sideways to the desired angle, or by using a bent tip. Such cuts may be made either by hand or machine, both in straight or irregular lines and with the same depth range as in normal right angle cutting. The usual angular limits of bevel and straight faced fillet cutting are indicated in Fig. 5.

Shapes—Straight lines, circles or contours of the utmost complexity are flame

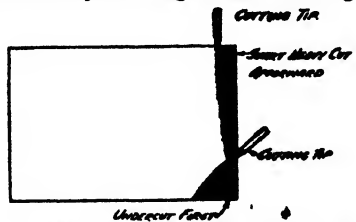


Fig. 4—Undercutting as an aid in starting a cut.

cut with equal ease, by either mechanical or hand guided torches. Flame cutting, in sharp contrast with most machine tool processes, has practically unlimited flexibility in this respect, Fig. 9.

Multiple Torch Cutting—In many applications of machine flame cutting, as many as six torches are used to cut a like number of identical shapes simultaneously. Concentric circles for flanges and the like often are cut in one operation, with two or more torches.

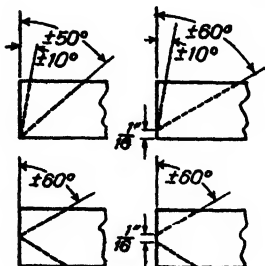


Fig. 5—Limits of bevel and fillet cutting.

Stack Flame Cutting—In addition to cuts made through a single thickness of material, flame cuts are made through several thicknesses simultaneously. This operation is known as "stack flame cutting" and offers a means of cutting numerous shapes simultaneously with a single torch, instead of employing multiple torch cutting.

The plates in the stack should be clean and flat, with edges in alignment where the cut is started. Their number should vary with the thickness of individual plates, to keep stack thickness within proper limit. They should be firmly clamped together as nearly as possible along the line of cut. In stack flame cutting thin plates, a "waster plate," having sufficient rigidity to lie flat while the cut is being made, usually is clamped on to prevent the top thin plate from buckling with the heat. It serves also to maintain ignition in the cut by its own combustion, thereby facilitating the speed of cutting in this kind of work.

Flame Cutting Techniques—Several different flame cutting techniques have been developed, for performing various cutting operations and for cutting different grades of ferrous metals. The International Acetylene Association in its Oxy-Acetylene Committee Publication, Section I, entitled "Oxy-Acetylene Cutting" defines five distinct flame cutting techniques. These are typified from the standpoint of flame movement in Fig. 6 and may be described as follows:

Type 1 Flame Cutting—This is the simple progressive type, universally used for

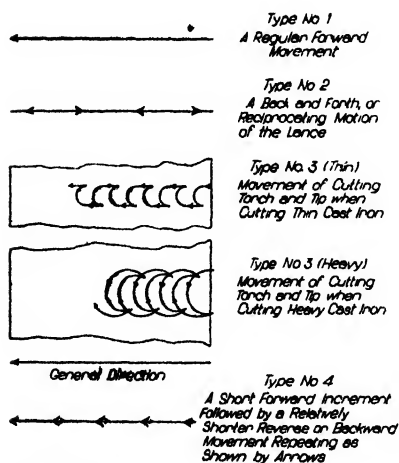


Fig. 6—Types of cutting techniques.

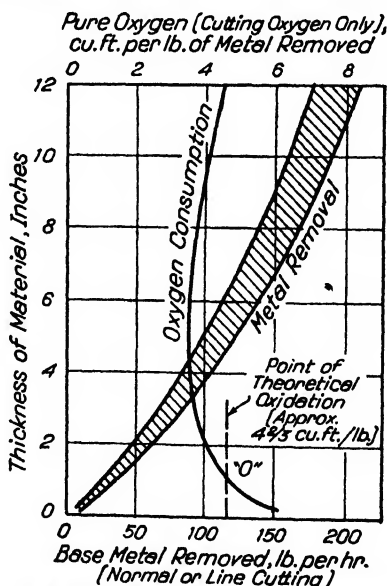


Fig. 7—Relationship between thickness, metal removed, and oxygen consumed.

carbon steels and other easily cut ferrous metals. The cut proceeds freely and regularly in a line and at the will of the operator. The technique consists in first preheating a spot to kindling temperature (1400-1600°F.) with the several small

preheating flames surrounding the cutting oxygen orifice. The cutting oxygen is then turned on and the cut started. Theoretically, preheating should be really necessary for starting only. In practice, however, preheating flames are maintained throughout the cutting operation, to insure continuity of cutting and high speed. Manipulation of the torch is merely that of holding it at correct height above the surface and advancing it at proper uniform speed along the line of cut, Fig. 6. The high velocity of the cutting oxygen stream confines it to a narrow path and holds its oxidizing action to within close limits. This makes accurate control possible. In practice, a considerable portion of the metal removed from the kerf is blown out in molten metallic form, unoxidized. This is particularly true with heavier cuts. Fig. 7 illustrates the relationship between thickness, metal removed and oxygen consumed in Type 1 flame cutting.

Type 2 Flame Cutting—Commercially, this is known as oxygen lance cutting. Practically all ferrous metals and many other materials can be cut or pierced with the oxygen lance. The lance ordinarily consists simply of a length of $\frac{1}{4}$ or $\frac{3}{8}$ in. I.D. size black iron pipe, with a globe valve on one end, connected to an oxygen hose, regulator and cylinder or manifold, so that only oxygen flows through the lance pipe.

Similar to Type 1 flame cutting, a spot is first preheated to kindling temperature, usually with a welding torch with large tip. Then the end of the lance is brought against the heated area and oxygen at about 40-50 psi. turned on. This oxidizes the metal and sufficient heat is produced to continue the cut or hole with oxygen alone, without oxy-fuel gas flames to facilitate the progress. The end of the lance is held in the cut or hole, so that the cutting oxygen stream emerges at the point of cutting or oxidation. This heats the end of the lance pipe, causing it to burn also. As the operation proceeds, the lance is consumed, ultimately requiring replacement by a new length of iron pipe. Oxidation of the lance itself requires only a minor portion of the oxygen consumed, while the heat of the burning lance assists the cutting.

Once started, the oxidation reaction is vigorous. It may be further intensified, if desired, by using a lance pipe of greater wall thickness, or by inserting one or more steel rods in the pipe. The thicker pipe and rod inserts both furnish additional fuel and heat, while the rods decrease the area of the effective opening in the lance pipe, thereby imparting greater velocity to the oxygen stream and increasing its eroding effect.

Oxygen lance cutting acts to extend the depth penetration range of standard cutting torch operations. It is seldom used alone but as an aid to Type 1 flame cutting in severing thick or heavy masses of metal. However, under proper conditions and set-up, oxygen lances can be employed independently. With various modifications, they are used for flame cutting large sections of cast iron, steel and other materials. For example, they serve to burn holes in salamanders and ladle chills, in which, after cooling, dynamite is inserted and exploded for final demolition. The opening of tap holes in blast and open hearth furnaces with the oxygen lance has become standard practice. In this operation, a spot of metal in the tap hole and the end of the lance pipe are both heated red hot with an oxy-acetylene welding torch. Oxygen is then allowed to flow through the pipe and impinge on the hot metal which is quickly pierced, allowing the molten metal to flow out.

Lancing usually consumes more oxygen per pound of metal removed, than other types of flame cutting. This, however, is offset by the greatly increased value of the cutting service as compared with other methods that can be used for such work. Obviously, the surface produced by Type 2 flame cutting, or lancing, is not as smooth as is obtained with Type 1 flame cutting. Nevertheless, surprisingly accurate holes can be pierced with the lance. Oxygen lance cuts should be made so that the slag and molten metal can flow out of the cut freely by gravity, wherever possible.

Type 3 Flame Cutting—This technique was developed especially for cutting cast iron. Considerably more preheat is used than in Type 1 flame cutting, both in starting and maintaining the cut. In addition, a definite flame oscillation is resorted to, which is necessary for cutting the cast irons, particularly those possessing carbon in the uncombined or graphitic state, as this resists flame cutting. The sidewise motion or oscillation of the flame is roughly in the form of half circles or new moons, advancing in short and regular intervals, as shown in Fig. 6, Type 3 (Heavy) when cutting heavy cast iron. A slight modification of the flame oscilla-

tion, also shown in Fig. 6, Type 3 (Thin) has been found more advantageous for cutting thin cast iron.

The resulting cut, therefore, may be termed a "worked cut," for the cast iron originally in the kerf has, in reality, been "worked out" by the oscillating technique. The latter, if regularly maintained, causes a constant stream of slag and molten metal to flow through the kerf, preheating the base metal in the kerf and preparing it for further oxidation and displacement as the molten products are removed. The cut naturally is somewhat rougher than a Type 1 flame cut, more of the metal having been removed by the mechanical eroding effect of the cutting oxygen

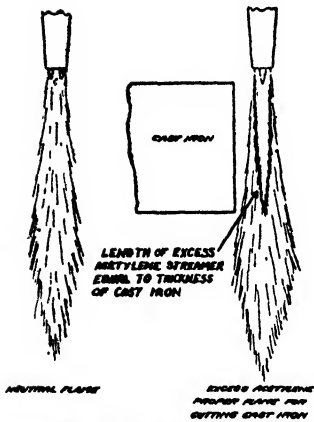


Fig. 8—Flame for Type 3 Cutting.

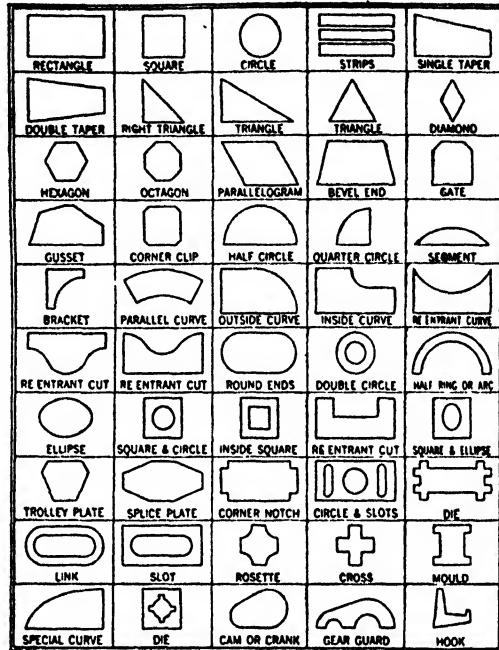


Fig. 9—Examples of shape cutting.

jet. Due to the wider kerf produced, more metal must be oxidized and oxygen and acetylene consumptions are greater than for Type 1 flame cutting.

Highly carburizing preheating flames are used in Type 3 flame cutting of cast iron; that is, the flames are adjusted to carry a considerable excess of acetylene, which appears as a long whitish feather in the flames beyond the small brilliant inner flame cone, Fig. 8. The length of the excess acetylene streamer should be approximately equal to the thickness of the cast iron. This flame adjustment aids in maintaining preheat in the cut, as the excess acetylene combines with cutting oxygen beyond the tip.

Type 3 flame cutting, or cast iron cutting, appears to be limited at present to demolishing castings, usually in basements or other inaccessible locations where they must be broken up before removal, or otherwise reduced in size, and to making alterations and repairs to machinery.

Type 4 Flame Cutting—For severing the so-called stainless steels, which resist ordinary techniques, a distinctive cutting technique, utilizing a different flame motion or oscillation from Type 3 flame cutting, has been developed. Here also, the flame is moved continually while cutting, but in a reciprocating manner in short strokes back and forth along the line of cut, Fig. 6, instead of sidewise. In starting a stainless steel cut, preheat is applied along the entire face or leading edge of the cut, from top to bottom, until it has been brought to a bright red color, in addition to preheating the usual spot at the top edge. Then the cutting operation

is started and progressed through the part by the forward and backward reciprocating motion already described, advancing the cut in short forward increments each time.

As in Type 3 flame cutting, the maintenance of a steady stream of liquid slag and molten metal is essential for a successful cut. Slag erosion is probably as important as any other single factor in cutting stainless steels. It determines the degree of uniformity in which cutting in these metals is attainable. Naturally, Type 4 cutting leaves a rough surface, calling for subsequent machining or grinding if a smooth finish is desired.

Type 5 Flame Cutting—This technique is developed around the use of metals of relatively high cutability to aid in the cutting of metals of lower cutability, similarly as fluxes are used in certain welding operations to increase the fusibility of refractory oxides. Different forms of this technique are employed, which, in the main, resort to cover, or cover and intermediate plates, known as "waster plates" of low carbon steels, placed as jackets or interlaminations between the resistant metals. These waster plates act to initiate good cutting conditions and relay them through the stack. The top and bottom plates sometimes are used merely to produce sharp cut edges in parts otherwise readily cuttable. In stack flame cutting, already described, their principal use may be for clamping a stack of thin plates firmly together. For certain operations, a light bead of low carbon steel is arc welded to the plate surface along the line of cut and the cut is made through this bead, which assists the cutting action in resistant metals. The bead is consumed in the cutting.

Another form of Type 5 in flame cutting employs a low carbon steel rod or bar at the point of cutting to supply additional heat and slag to a cut in a resistant material, thereby supplementing the work of the cutting torch. The bar or rod can be moved at the will of the operator, to be available at or adjacent to the critical point of cutting. Iron filings also can be used. This method often enables castings or resistant materials to be cut quite readily.

Any of the previously described flame cutting techniques may be employed in Type 5 flame cutting, depending on the resistance of the material to the process.

Table V
Effect of Alloying Elements on Gas Cutting of Steel

Element	Effect
Aluminum	Aluminum content does not hinder flame cutting. However, an aluminum content of 10-15% resists flame cutting either hot or cold, except where special technique is used.
Carbon	Carbon in unalloyed steels up to 2% permits of flame cutting by simple progressive procedure (Type 1 technique). However, steels containing more than 0.30% carbon should be preheated to 500-600°F. before cutting, or heated, after cutting, before the cut surface cools to normal temperature to prevent hardening and cracking at edges. Quality of cut is affected by both amount and form of carbon content. Graphite and cementite (Fe_3C) tend to hinder cutting, but cast irons containing 4% carbon are cut successfully by special technique (Type 3).
Chromium	Chromium contents up to 1½% have no adverse effect. Steels with 4-6% chromium also may be cut by Type 1 technique, provided low intensity carburizing preheating flames are used. Where the chromium content is 10% or more, special cutting technique is required to produce a complete cut (Type 4 technique).
Copper	Copper up to 3% in steel permits of easy flame cutting.
Manganese	Manganese content up to 14%, with 1.3% carbon, allows for good cutting. However, high manganese steels require preheating before cutting to prevent cracking.
Molybdenum	Molybdenum content of 0.25%, as in chromium-molybdenum aircraft steels, does not hinder cutting. But a steel with 5.5% molybdenum, 8% tungsten, and 1% carbon is uncuttable, either hot or cold, unless special techniques are employed.
Nickel	Nickel in steel up to 7% does not hinder good flame cutting. Steels with 34% nickel have been cut where the carbon content was below 0.50%.
Phosphorus	Phosphorus content up to 2% does not prevent good gas cutting.
Silicon	Silicon in steel up to 2.80% permits of cutting by simple progressive method. Transformer iron, containing up to 4% silicon, can be gas cut, but high silicon content reduces speed. Precautions in preheating and cooling are necessary with certain of these steels in the upper ranges of carbon and manganese to prevent or modify air hardening tendencies.
Sulphur	Small amounts, such as are normally present in steels, have no effect. With higher percentages of sulphur, the rate of gas cutting is reduced and sulphur dioxide (SO_2) fumes are produced.
Tungsten	Tungsten up to 10% does not hinder flame cutting of steels, which contain also 5% chromium, 0.2% nickel and up to 0.8% carbon. A 17% tungsten content necessitates preheating before cutting and a procedure similar to cast iron cutting (Type 5 technique).

At times, flux cutting enables resistant materials to be cut by Type 1 flame cutting, which would otherwise require a more tedious technique.

Cutability of Ferrous Metals—Certain alloy steels contain chromium, nickel, and other elements in sufficient amounts to render them considerably more difficult to cut than carbon steels. The effect of various alloying elements on the cutability of steel, as reported by various authorities, is summarized in Table V.

Types of flame cutting techniques, as described in previous sections, which are employed with various ferrous metals are given in Table VI.

Table VI
Flame Cutting Data for Ferrous Metals¹
Cutting Technique² and Heat Treating Practices³

Name of Metal	Approx. Carbon Content, %	Cutting Technique ²					Preheat Flames ⁴
		Type No.					
		1	2 ¹¹	3	4	5	
Iron (low carbon).....	0.04	C					
Carbon steels ⁵							
Low carbon	0.10-0.30	C ⁶					
Medium carbon	0.30-0.50	P or HT					
High carbon	0.50-1.60	HT					
Tool steel	0.90-1.10	HT					
Cast iron							
Gray iron	2.75-3.75		C ¹⁴	C ¹⁴		C ¹⁴	Car.
Malleable iron	2.50		C ¹⁴	C ¹⁴		C ¹⁴	Car.
Alloy cast iron	Any		C ¹⁴	C ¹⁴		C ¹⁴	Car.
Durlon (Si Approx. 15.0%).....	0.75		C ¹⁴	C ¹⁴		C ¹⁴	Car.
Manganese steels							
SAE T-1330 (Incl. Mn structural).....	0.25-0.35	P or HT					
SAE T-1350	0.45-0.55	HT ⁷					
Hadfield's (10.0-14.0% Mn).....	1.00-1.50	P					
Silico-manganese (0.80-2.20 Si).....	0.45-0.70	HT					
Silicon steels							
Structural (0.20-0.30 Si).....	0.25-0.40	HT					
Transformer (up to 4.00% Si).....	0.10 max.	P or HT					
Nickel steels							
SAE 2015 (0.40-0.60 Ni).....	0.10-0.20	C					
SAE 2115 (1.25-1.75 Ni).....	0.10-0.20	C ⁷					
SAE 2315 and 20 (3.25-3.75 Ni).....	0.10-0.25	C ⁷					
SAE 2330 to 50 (3.25-3.75 Ni).....	0.25-0.35	HT					
High nickel (34.0 max. Ni).....	0.50 max.			C ⁸		C	
Nickel-chromium steels							
SAE 3115 (0.45-0.75 Cr).....		C					
SAE 3120-50 (0.45-0.75 Cr).....		HT					
SAE 3215-50 (0.90-1.25 Cr).....		HT					
SAE 3312-40 (1.25-1.75 Cr).....		HT					
SAE 3415-50 (0.60-0.95 Cr).....		HT					
Molybdenum steels							
SAE 4130-50 (0.50-1.10 Cr) ⁹	0.25-0.55	HT					
SAE 4615 (1.65-2.00 Ni).....	0.10-0.20	C ⁹					
SAE 4620-40 (1.65-2.00 Ni).....	0.15-0.45	HT					
SAE 4815-20 (3.25-3.75 Ni).....	0.10-0.25	HT					
Chromium steels							
SAE 5120 (0.60-0.90 Cr).....	0.15-0.25	P or HT					
SAE 5140-50 (0.80-1.10 Cr).....	0.35-0.55	HT					
SAE 52100 (1.20-1.50 Cr).....	0.95-1.10	HT					
4.00-6.00 Cr steel.....	0.25 max.	HT					Car.
Stainless steels							
Low carbon chromium (12-18. Cr).....	0.12-				C ¹³	C ¹²	Car.
High carbon chromium (12-18. Cr).....	0.30-0.60				C ¹³	C ¹³	Car.
Chromium-nickel (7-10. Ni) (16-20. Cr).....	0.05-0.20				C ¹³	C ¹²	Car.
Chromium-vanadium steels							
SAE 6115-20 (0.80-1.10 Cr).....	0.10-0.20	C ⁷					
SAE 6125-95 (0.80-1.10 Cr).....	0.20-1.05	HT					
Tungsten steels							
SAE 71360 (12.00-15.00 W).....	0.50-0.70			C ⁹		C	
SAE 71660 (15.00-18.00 W).....	0.50-0.70			C ⁹		C	
SAE 7260 (1.50-2.00 W).....	0.50-0.70	C ^{9, 10}					
Vanadium steel (0.15% V. Min.).....	0.90	HT					
Aluminum steel ¹² (below 10% Al).....		C					

¹The data apply to metal in the wrought, rolled, and cast condition unless otherwise noted. Preheating of any steel will, in general, improve the economy of cutting and prevent acute hardening. For carbon steels, heat treatment in one form or another is usually employed where the carbon content exceeds 0.30% provided the cutting is conducted at normal temperatures 60-80°F. If the temperature of the metal is lower than this, heat treating may have to be employed at a lower carbon content to preserve or re-establish desired physical properties. Where the letters CP or C-HT are given, it is meant that the material is cuttable cold, but requires either preheating

(Continued)

or reheating, as the case may be, to prevent damaging the cut surface or to preserve or restore commercial properties.

*The technique of cutting varies for different grades of steel. See the description of the five distinct types in the text.

*Heat treating practices employed for those grades which are unduly hardened by the normal application of flame cutting are listed in the table under the following classifications:

C—denotes that metal may be safely cut at room temperatures.

P—denotes that metal should be preheated before cutting to prevent hardening of the metal in the face of the cut. Usual preheating temperatures range from 500-900°F. Preheating is also used for certain grades to facilitate cutting.

HT—denotes heat treatment, furnace or otherwise, subsequent to cutting to improve or recondition the structure of the cut surface, provided the material is kept warm between the time of cutting and heat treatment.

*Unless otherwise indicated neutral preheating flames are to be assumed. However, appreciably higher preheating temperatures may be obtained by adjusting these flames for an excess of oxygen (oxidizing). Therefore, for cases where additional preheat is desired, oxidizing preheating flames may be used wherever neutral flames are indicated. Considerable economies are sometimes obtainable with oxidizing flames in which the ratio of oxygen to acetylene is about 1.7 or 1.8 to 1.

Car.—Denotes carburizing flame. A carburizing flame is one carrying an excess of fuel gas over that required for complete combustion.

*The addition of normal amounts of copper (up to 3.00%) does not interfere with the type of cutting nominally employed for the grade of steel in question. The addition of copper, however, does increase hardening of the cut surface necessitating introduction of heat treatment at a lower point in the aggregate of hardening alloys than would otherwise prevail.

*Grades SAE X-1314, X-1315 may harden perceptibly if carbon runs to the high side and is cut at normal or lower temperatures.

*Heat treating, after cutting, may be necessary if carbon runs to high side.

*There are no data available as to heat treatment for this grade, if necessary.

*Including SAE 4340 and 4315.

*Tungsten evidently may go to 10% with Type No. 1 cutting technique.

*All grades which respond to Type No. 1 cutting technique will readily respond to Type No. 2 technique either in conjunction with Type No. 1 technique or separately. The heat treatment for Type No. 2 corresponds to that respectively for Type No. 1.

*Heat treatment usually necessary to counteract harmful effects of the heating produced during the cutting operation unless the metal contains a stabilizing element to prevent such heat effects.

*Aluminum steel containing approximately 1% Al, 1% Cr and 0.50% Mo is reported to be cuttable by Type No. 1 technique. Heat treatment would depend upon the carbon content.

*The cut surfaces of the cast irons in heavy sections are hardened by the cutting operation and should be heat treated if they are to be machined after cutting.

Table VII

Hand Flame Cutting Table for ½-12 In.

Thickness for Clean, Mild Steel—Not Preheated—Type 1 Cutting Only

Thick- ness of Steel, in.	Diameter of Cutting Orifice, in.	Oxygen Pressure, psi.	Cutting Speed, in. per min.†	Gas Consumptions*—			
				Per hr.		Per linear ft.†	
				Oxygen, cu.ft.	Acetylene, cu.ft.	Oxygen, cu.ft.	Acetylene, cu.ft.
¼	0.0380-0.0400	15-23	20-30	45-55	7-9	0.37-0.45	0.06-0.07
¼	0.0380-0.0595	11-20	16-26	50-93	9-11	0.63-0.72	0.08-0.11
½	0.0380-0.0595	17-25	15-24	60-115	10-12	0.80-0.96	0.10-0.13
¾	0.0465-0.0595	20-30	12-22	66-125	10-13	1.10-1.14	0.12-0.17
¾	0.0465-0.0595	24-35	12-20	117-143	12-15	1.43-1.95	0.15-0.20
1	0.0465-0.0595	28-40	9-18	130-160	13-16	1.78-2.89	0.18-0.29
1½	0.0595-0.0810	-40	6-	.....	.....	.....	.....
2	0.0670-0.0810	22-50	6-13	185-231	16-20	3.55-6.16	0.31-0.53
3	0.0670-0.0810	33-55	4-10	240-290	19-23	5.80-12.00	0.46-0.95
4	0.0810-0.0860	42-60	4-8	293-388	21-26	9.70-14.64	0.65-1.05
5	0.0810-0.0860	53-70	3.5-6.4	347-437	24-29	13.66-19.83	0.91-1.37
6	0.0980-0.0995	45-80	3.0-5.4	400-567	27-32	21.00-26.70	1.19-1.80
8	-0.0995	60-77	2.6-4.2	505-615	31.5-38.5	29.30-38.84	1.83-2.42
10	-0.0995	75-96	1.8-3.2	610-750	36.9-45.1	46.90-64.20	2.67-3.84
12‡	0.1200	69-86	1.4-2.6	720-880	42.3-51.7	67.70-103.00	3.98-6.05

*As the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data, therefore, have been omitted from this table. For acetylene pressure data, see cutting apparatus manufacturers' charts.

†Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, dirty or poor material. Highest speeds and lowest gas consumptions per linear foot are for experienced operators, long cuts, clean and good material.

‡Beyond 12 in. thickness, the critical data of manual cutting practices are greatly affected by the condition of the metal and the skill of the operator, resulting in wide ranges of data. In view of this, the table has been terminated at the 12 in. thickness.

The reader is referred to Table VIII, giving data on Machine Cutting wherein the thickness range has been extended to 20 in.

Hand Flame Cutting—Many variables affect free hand flame cutting performance. However, the range of fair average practice in free hand oxy-acetylene flame cutting of mild steel, not preheated, is given in Table VII. Oxygen and acetylene consumptions for cutting the various thicknesses up to and including 18 in. are listed, both in cu. ft. per hr. and cu. ft. per linear ft. of cut.

Free Hand "Guided" Flame Cutting—This includes such operations as circle cutting and drawing the torch head along a bar or straight edge which acts as a guide. Circles or discs can be cut accurately with a straight head hand torch, using a circle cutting attachment consisting of a clamp, radius rod and adjustable center point. Another attachment has small wheels which rest and roll on the surface of the work.

Flame Cutting Machines—Flame cutting machines are comparable with machine tools. They are capable of making flame cuts with jig-saw flexibility and of such high quality and accuracy the edges frequently require no further finishing.

Straight Line Machine Flame Cutting—Straight line machine flame cutting is even simpler than free hand flame cutting. Once the machine and gas pressures have been set the torch follows the line of cut automatically. As the cut progresses, the operator watches the drag and the flow of slag or oxide to prevent pocketing or other defects from developing. For oxy-acetylene machine flame cutting of mild steel, speeds and gas pressures should be adjusted within the ranges given in Table VIII.

Table VIII
Machine Flame Cutting Table for 1/8-20 In.
Thickness for Mild Steel—Not Preheated—Type 1 Cutting Only†

Thick- ness of Steel, in.	Diameter of Cutting Orifice, in.	Oxygen Pressure, psi.	Cutting Speed, in. per min.†	Gas Consumptions*			
				Per hr.		Per linear ft.†	
				Oxygen, cu.ft.	Acetylene, cu.ft.	Oxygen, cu.ft.	Acetylene, cu.ft.
1/8	0.0250-0.0400	15-23	22-32	40-55	7-9	0.34-0.36	0.05-0.06
1/4	0.0310-0.0595	11-35	20-28	45-93	8-11	0.45-0.66	0.08-0.08
3/8	0.0310-0.0595	17-40	19-26	82-115	9-12	0.86-0.89	0.09-0.09
1/2	0.0310-0.0595	20-55	17-24	105-125	10-13	1.04-1.24	0.11-0.12
5/8	0.0380-0.0595	24-80	18-22	117-159	12-15	1.45-1.55	0.14-0.16
1	0.0465-0.0595	28-55	14-19	130-174	13-16	1.83-1.86	0.17-0.19
1 1/2	0.0670-0.0610	-55	12-15	-240	14-18	3.20-	0.23-0.24
2	0.0670-0.0610	22-60	10-14	185-260	16-20	3.70-3.72	0.29-0.32
3	0.0810-0.0860	33-50	8-11	240-332	18-23	6.00-6.04	0.42-0.45
4	0.0810-0.0860	42-60	6.5-9	293-384	21-26	8.53-9.02	0.58-0.65
5	0.0810-0.0860	53-65	5.5-7.5	347-411	23-29	10.97-12.62	0.77-0.84
6	0.0980-0.0995	45-65	4.5-6.5	400-490	26-32	15.10-17.78	0.98-1.16
8	0.0980-0.0995	60-90	3.7-4.9	505-625	31-39	25.52-27.30	1.59-1.68
10	0.0995-0.1100	75-90	2.9-4.0	610-750	37-45	37.50-42.10	2.25-2.55
12	0.0110-0.1200	69-105	2.4-3.5	720-880	42-52	49.70-60.00	2.97-3.50
14	0.0110-0.1200	-105	2.0-3.2	830-1045	48-59	65.20-83.00	3.69-4.80
16	0.1285-0.1600	-110	1.8-3.0	935-1360	57-70	90.60-104.00	4.67-6.33
18	0.1495-0.1600	-120	1.7-3.0	1045-1680	65-83	112.10-123.00	5.53-7.65
20	0.1610-0.2000	-135	1.5-3.0	1155-2050	75-89	136.70-154.00	6.60-10.00

*As the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data, therefore, have been omitted from this table. For acetylene pressure data, see cutting apparatus manufacturers' charts.

†Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, dirty or poor material. Highest speeds and lowest gas consumption per linear foot are for experienced operators, long cuts and clean and good material.

‡The apparent inconsistencies which will be noted in some of the columns in the table are due to the fact that there does not exist a straight line relationship between the elements of pressure, speed, and orifice sizes for the range of apparatus data from which this table was devised.

Shape Machine Flame Cutting—Regular or irregular shapes, of almost any size or thickness, no matter how complex, are machine flame cut with ease. The process has jig-saw flexibility. Shape cutting machines are mostly motor driven. Some have tracing devices which are manually guided around the outline of a drawing or templet of the required shape. One or more torches mounted on the machine duplicate the motion of the tracing device over the work, thereby flame cutting the shape traced. Other machines are fitted with motor driven guide rollers, which automatically follow a templet of the required shape, simultaneously controlling the movement of the torch so as to flame cut the same shape. Motor driven magnetized rollers, which adhere to steel templates as they advance automatically around the

contour, are a feature of certain machines. Some typical shapes, for which machine flame cutting is adapted, are illustrated in Fig. 9.

Circular Machine Flame Cutting—Most flame cutting machines can be adapted to circular cutting. With some, a radius rod with an adjustable center point is furnished. The point is placed in a center punch mark at the center of the circle and the machine and cutting torch travel around the circumference at the radius set. A short "lead in" cut through the scrap is customarily made, so as to have the finished cut smooth and unmarred at the starting point.

Precision Machine Flame Cutting—One machine flame cutting technique which produces especially high quality and accurate cuts is sometimes distinguished by the name "precision machine flame cutting." It will be noted in Fig. 3 that precision machine flame cutting has been set up as a separate division of machine flame cutting, to distinguish it from standard machine flame cutting, which is not so refined a process.

While the technique described under Type 1 cutting is, generally speaking, the one followed for precision machine flame cutting, closer adjustments of pressures and speed are required than for standard machine flame cutting. Cut surfaces true to within 0.003 in. as to cross sectional squareness for a 1 in. thickness have been attained by this method. For thicker material, cross cut tolerances increase approximately in proportion to the thickness. The cross cut tolerances for 1, 2, 4 and 6 in. thicknesses for precision machine flame cutting are shown in Fig. 10. These tolerances are not generally commercially available at this time.

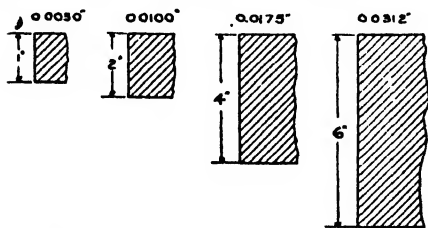


Fig. 10—Cross cut tolerances, precision machine cutting practices.

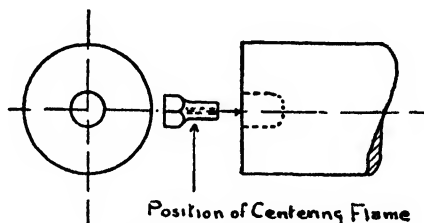


Fig. 11—Flame drilling.

Machine Flame Cutting Table—The range of fair average practice in machine oxy-acetylene flame cutting of mild steel, not preheated, is given in Table VIII. Oxygen and acetylene consumptions for cutting various thicknesses up to and including 20 in. are listed, both in cu. ft. per hr. and cu. ft. per linear ft. of cut.

Flame Machining Operations—In flame machining, each operation is more or less a problem in itself, calling for a co-ordination of nozzle tooling and metallurgical control. Various types of flame machining operations have been included at the right-hand side of Fig. 3. It will be noted that these are termed planing, milling, turning, drilling, and boring, similar to corresponding machine tool operations. Subclassifications of these operations also are given in the chart. Not all of these operations have been commercialized up to the present time, however, some being still in the development stage.

Flame Planing—There are several types of tangential cuts which classify under the heading of "flame planing." The principal differences are primarily the character of application and the tolerances or degrees of surface regularity attained or permitted. Flame planing can be either manual or mechanical. The subclassifications are:

1. **Deseaming or Scarfing**—This process of flame planing is used in the steel mills for removing cracks or seams in billets, slabs, and rounds. It also is employed in steel foundries for exploring and cleaning out cracks and sand holes in castings.

2. **Hogging**—This application of flame planing performs the functions of removing superfluous metal in steel castings, either purposely provided or caused by defective conditions at the time of pouring, as well as those of removing risers and sprues whose location or character is such as to make it difficult or impossible to dispose of them by ordinary or Type 1 flame cutting.

3. **Surface Planing**—This operation is a step beyond the practices of "Deseaming," in that the cuts are caused to be adjacent to one another, thus enabling the removal of wide surfaces. When done mechanically, the dimension tolerances as to depth and width of cut can be kept to within $\frac{1}{16}$ - $\frac{1}{8}$ in. of the finished surface,

Flame Drilling and Punching—Fig. 11 shows a method used for flame drilling a round hole in the end of a billet for centering or piercing purposes. The dimensions of the finished hole can be made uniform and its walls straight sided, provided the nozzle or tip is properly held during the drilling operation.

The oxygen lance, described under Type 2 flame cutting, is also a valuable tool for flame drilling operations, particularly those of considerable depth, beyond the reach of cutting tips.

Rivet Cutting—Flame drilling has proven successful for rivet cutting by surface oxidation of heads. Cutting tips used for this operation have large cutting oxygen orifices of expanding, low pressure, low velocity type, together with high intensity preheating flames. The tip is held in line with the rivet, close to the head, so that preheating flames impinge on its center. As soon as a spot is heated bright red, the cutting oxygen is turned on slowly. This quickly oxidizes a crater in the head and consumes it. The shank of the rivet is then knocked out of the hole.

Flame Boring—Rough boring can be accomplished by means of a compound setting of the cutting flame. Application of this process depends largely on tooling to prevent the slag and molten metal from the cuts from interfering with the cutting and the operation of the cutting nozzle.

Underwater Cutting—There are two methods for torch cutting of submerged metals.

One method employs an oxy-hydrogen cutting torch fitted with a bell or skirt around the tip, which is filled with compressed air to supply additional or atmospheric oxygen for combustion of the hydrogen, and also to hold the water away from the preheating flames and the cutting area.

The other method consists in using oxy-acetylene torches for underwater cutting at shallow depths (less than 35 ft.). At greater depths the fuel gas pressure required to overcome the hydraulic head is beyond the safe operating pressure of acetylene, and hydrogen is used. When using acetylene, considerably more compressed air must be supplied.

Only divers who have been specially trained in underwater cutting can practice it successfully. The tips are liable, for some obscure reason, to side perforations while operating. Quite a little underwater cutting has been done with hydrogen at depths of 135 ft. or more on sunken submarines, bridge caissons, submerged wrecks, and steel piling.

Safety Rules—Certain precautions must be observed for the safe handling and operation of gas cutting tools and appurtenant equipment. Standard Rules and Regulations have been promulgated by the cutting industry in co-operation with regulatory bodies dealing with the public and workers' safety. In "Safe Practices Bulletin No. 23," published by the National Safety Council, and in "Regulations for the Installation and Operation of Gas Systems for Welding and Cutting," issued by the National Board of Fire Underwriters, the subject of general safety as it applies to gas welding and cutting processes is well covered.

Electric Arc Cutting—The process of electric arc cutting is purely one of applying the heat energy of the electric arc to melt the metal along the desired line of cut. Due to the extremely high temperature developed in the electric arc, it can be used to fuse almost any electrical conducting material and, in this way, is employed for cutting metals. Arc cutting is, of course, not a true cutting process, since the metal is merely melted away. It does not equal gas cutting from the standpoint of smoothness, quality, or accuracy of cut surfaces, and hence, is not used where high quality, accurate cuts are required. It is, however, useful where smooth, uniform cut surfaces are not essential and merely severing is the main object, as in scrapping operations. Arc cutting is also used for metals not easily cut in any other manner, such as cast iron, manganese steel, and large sections of non-ferrous metals. It is particularly applied to cutting risers of large manganese steel castings. Rivet cutting and hole piercing are other operations for which arc cutting is used.

Carbon Arc Cutting—This process consists essentially of drawing an arc between a carbon or graphite electrode and the material to be cut. Direct current is generally used, with the carbon electrode negative (straight polarity), although alternating current can be used also. Graphite electrodes are preferred to carbon electrodes, as they have a much longer service life and retain a point longer. The latter is essential for clean, smooth cuts. The heavy currents used for arc cutting make ordinary electrode holders unsuitable, except for light work. Special holders

with long shank, special gripping mechanism, and hand protecting shield are recommended.

Manipulation of cutting arc, when cutting plates of $\frac{1}{4}$ in. thickness or less, consists simply in advancing along the line of cut at a rate equal to that at which the metal is being melted away. The most smooth and uniform cuts are obtained with the plate in the horizontal plane, but the operation may be done with the plate in inclined or vertical position also. In horizontal cutting, the electrode is held vertical or pointed slightly forward. For inclined or vertical cutting, the electrode is pointed downward. When cutting materials heavier than $\frac{1}{4}$ in., the vertical face of the cut is progressively melted away by working from top to bottom, thereby having the bottom of the cut advanced slightly ahead of the top of the cut and producing an undercut which permits the molten metal to run out more easily. Skilled operators can make narrower cuts. The width and speed of the cut increase with the current and the electrode diameter. Recommended current values for different size graphite electrodes are given in Table IX.

Table IX
Current Values for Arc Cutting

Electrode Dia., in.	Current Values in Amperes
$\frac{1}{4}$	Up to 200
$\frac{3}{8}$	200-400
$\frac{1}{2}$	300-600
$\frac{5}{8}$	400-700
$\frac{3}{4}$	600-800
$\frac{7}{8}$	700-1000
1	800-1200

Rivet Cutting by Carbon Arc Process—The best results are obtained with the plates in the vertical position. If the plates are in the horizontal position, and rivets are being cut from the top of the plate, the molten metal is removed by an air blast or by mechanical means. If rivet heads are cut underneath the plate, the molten metal is removed by gravity, as when removing rivets from vertical plates. Where plates are to be salvaged the arc should not be struck on them as it is apt to burn a depression. Rather the arc should be struck on the rivet head and rotated slightly, care being taken not to concentrate it too long at the periphery of the rivet head. For rivet cutting, a $\frac{1}{4}$ - $\frac{5}{8}$ in. graphite electrode using 400-600 amperes current is recommended.

Arc Cutting with Coated Electrodes—The application of heavily coated electrodes to cutting is not always an economical process, but has certain merits, particularly where no oxy-acetylene cutting torch or graphite electrode is available. Electrodes with either gaseous or slagging type coatings can be used, but the latter give better results because they will handle higher current densities. Plates up to $\frac{1}{4}$ in. thick can be cut by simply advancing the electrode along the line of cut. On heavier plates the electrode is pointed forward and moved from the top to the bottom of the cut, so as to keep the bottom slightly ahead. Electrodes smaller than $\frac{3}{8}$ in. dia. are not suitable for arc cutting. The width of the cut is approximately constant for all electrodes up to $\frac{1}{4}$ in. dia. Alloy steels and many nonferrous metals can be readily cut by the coated electrode cutting process.

Piercing Holes with Coated Electrodes—Coated electrodes can also be used to pierce holes in plates. This process is applied in cases where a hole is desired and it is impractical to punch or drill it, or use gas cutting. The operation depends on the formation of a crater at the end of the electrode which results from the steel core melting faster than the surrounding coating. This permits pushing the electrode end against the plate without shorting the circuit. Consequently, there is still a gap between the metal conductors and the electric arc does not become extinguished. High current is applied to the electrode. The arc is struck at the point where the hole is to be pierced and the electrode given a circular motion, equal to the diameter of the hole to be pierced, until the surface of the metal is melted. Then the electrode is pushed down against the molten metal and the circular motion continued. This will cause a hole to be melted through the plate.

Heat Treatment

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Principles of Heat Treatment of Iron and Steel*

By E. S. Davenport*

Introduction—The purpose of this article is to outline the principles underlying the heat treatment of ferrous materials. These fundamental principles are used when one intentionally alters the mechanical properties of steel by heat treatment in order to make it more serviceable for some particular purpose. The general aim of heat treatment is to *improve* some property or combination of properties as compared to the condition of the material prior to the heat treatment; for example, if the properties in the hot rolled, cold rolled, or cast condition are not suitable for some particular purpose a heat treatment is applied to develop the desired structure and properties. A misunderstanding of the principles involved may result in a heat treatment which develops *inferior* properties instead of the intended improvement. It is necessary, therefore, that anyone attempting to devise a treatment for a new material or for the development of new combinations of properties, should have a thorough grasp of the fundamentals of the subject.

An article on the subject of heat treatment of metals in general appears on page 198. The present article confines itself to the heat treatment of steel and, moreover, is limited to a discussion of principles. For more specific information on the heat treatment of particular classes of steels, reference may be made to other articles in this volume.

General Principles—The following definition of heat treatment has been adopted by the S.A.E., A.S.T.M., and the A.S.M.

Heat Treatment—An operation or combination of operations, involving the heating and cooling of a metal or an alloy in the solid state for the purpose of obtaining certain desirable conditions or properties.

Note—Heating and cooling for the sole purpose of mechanical working are excluded from the meaning of this definition.

In spite of this "Note" it should be borne in mind that the cooling from hot working operations, such as rolling or forging, may, and often does, constitute a heat treatment just as much as if a separate heating and cooling cycle were applied. For many purposes, of course, the structure and properties resulting from such cooling may not be those desired, in which case further heat treatment is necessary.

It is assumed that the reader has a good working knowledge of the iron carbon diagram and the allotropy of the element iron, and recognizes the fact that the whole art and science of the heat treatment of steel is based upon the fact that there are two forms of iron: Alpha (ferrite) and gamma (austenite). It is the difference in solvent power of these two forms of iron for carbon and other alloying elements which places at our disposal the wide range of properties capable of being developed by heat treatment in ferrous materials.

In general, all heat treating processes involve two fundamental operations: A heating cycle, and a cooling cycle. A third factor—the element of *time* at one or more temperatures either in the heating, cooling or tempering cycle—must be taken into consideration in devising a heat treatment schedule for any particular steel. Some of the questions which must be answered in developing such a schedule are: How hot and at what rate should the steel be heated? How long should it be held at temperature? At what rate should it be cooled? Is the heat treatment to be considered as finished at the end of the cooling cycle or is a tempering treatment required? If tempering is necessary, what heating, cooling, and time-temperature cycles are to be followed? Let us now consider these questions in somewhat greater detail and attempt to arrive at answers from the viewpoint of general principles. It is realized that, in practice, the size and shape of the part being treated must be taken into account; but except where otherwise noted, this factor will be neglected in the following discussion as it does not affect the principles involved. Articles dealing more fully with this aspect of heat treatment appear elsewhere in this volume (Relation of Design to Heat Treatment, page 214, Mass Influence in Heat Treatment, page 512).

Heating—The first step in the heat treatment of steel is the heating of the material to some temperature either in or above the transformation range in order

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to put the iron in the gamma condition; the carbon and other elements are thus caused to dissolve in the gamma iron and to form the homogeneous solid solution, austenite. The solution of these elements may be either partial or complete, depending upon the time-temperature cycle. This austenite solid solution is the raw material out of which we build the final structure of ferrite and carbide in the subsequent cooling, or cooling and tempering operations.

Heating Rate—For many purposes the rate of heating is not as important as certain other essential features of the heat treating cycle such as, for example, maximum temperature, time at temperature, and rate of cooling. The initial condition of the material, with respect to internal stress produced by cold work or otherwise, may have an important bearing on the optimum heating rate because of its influence on distortion and cracking, and on the initial size and growth characteristics of the austenite grains; moreover, the volume change accompanying the alpha to gamma transformation as the metal passes through the transformation range must be taken into consideration in selecting a heating rate. Hard, brittle, highly stressed materials, such as steels in the martensitic or fully hardened condition, should be heated more slowly and carefully than is necessary for stress-free materials; otherwise cracking may occur. On the other hand, materials which have been subjected to a certain amount of cold working may exhibit a tendency to germinative or excessive grain growth when heated slowly through the transformation or recrystallization range; in such cases a rather rapid rate of heating through the germinative temperature range is indicated if excessive grain growth is to be avoided.

The thermal conductivity of the material, the nature of the furnace atmosphere (whether scaling or nonscaling) and the thickness of section, all have an influence on the behavior of the steel in relation to the rate of heating. The difference in temperature rise within thick and thin sections of articles of variable cross section is, of course, an ever present problem in practical heat treating operations; whenever possible, provision should be made for retarding the heating of the thinner sections in order to minimize thermal stress and distortion. In general, the heating rate should be such as to avoid injury to the material through excessive thermal and transformational stresses, but the possibility of germinative grain growth should be kept in mind. Indeed, uniformity of proper temperature throughout the material is the ultimate objective of the heating cycle; in most instances this uniformity will be attained more safely, and with less over-all damage to the steel, by slow heating than by fast heating.

Maximum Temperature—The selection of the maximum temperature will be determined to some extent by the chemical composition of the steel, the proportion of carbide or ferrite it is desired to put into solution in the austenite, and the maximum permissible austenite grain size if the latter has been defined or specified. In general, the higher the temperature, within limits, the greater the solubility of the phases (carbide or ferrite) and the greater the rate at which they are dissolved in the austenite; likewise, the higher the temperature, other things being equal, the larger the austenitic grain size.

For plain carbon, hypoeutectoid steels (below about 0.85% carbon) a temperature just above the upper transformation or critical temperature (A_3) is usually recommended. At this temperature (A_3), which, of course, varies with the carbon content of the steel, the transformation from alpha to gamma on heating is just completed, that is, all of the carbide and proeutectoid ferrite is in solid solution; thus maximum solubility of the constituents is achieved with minimum growth of the austenite grains. As the temperature is raised above the A_3 for any given steel, the austenite grains begin to grow; such grain coarsening is sometimes desirable for improving machinability; less frequently it is employed to increase hardenability (depth of hardening) although deeper hardening can usually be achieved better by other means.

For plain carbon, hypereutectoid steels (above about 0.85% carbon) a temperature between the lower transformation or critical temperature (A_1) and the upper critical (A_{cm}) is usually recommended. The upper critical line (A_{cm}) in the iron-carbon diagram rises so steeply with increasing carbon content above 0.85% that an excessively high temperature may be required to dissolve all the proeutectoid carbide in the austenite; this tends to develop undesirably coarse austenite grain size with consequent deep hardening and cracking effects. If it is desired to take full advantage of the hardening effect of the carbon and of the alloy content, it may be necessary to have most of the carbide in solution, in which case a tempera-

ture just at, or slightly above, the A_{cm} temperature must be employed; otherwise, it may be preferable to leave some of the carbides undissolved in order to restrain austenite grain growth and to act as transformation nuclei on cooling; when this is done a part of the potential hardenability of the steel is sacrificed in order to limit or control grain growth and depth of hardening. Undissolved carbides are almost always present to some extent in the austenite of alloy steels containing the reluctantly-soluble carbides of elements such as chromium, vanadium, molybdenum, and tungsten; excessively high temperature or an absurdly long heating period would be required to put all of these carbides into solution.

To summarize then, the maximum temperature in the austenitic range should be just high enough to achieve the necessary extent of solution of the constituents, ferrite or carbide, but no higher. The austenite must be held long enough at temperature to become essentially homogeneous and rich enough in carbon, and in such alloying elements as may be present to bring about the desired hardening in the subsequent cooling operation; yet excessive growth of the austenite grains should be avoided, in so far as possible. If for any reason, a coarse austenitic grain size is desired, a higher maximum temperature should be used.

Time at Maximum Temperature—In general, time at temperature has an influence similar to maximum temperature, as discussed in the preceding section. In any heat treating process *temperature* and *time* must be considered simultaneously since practically all changes in metals take place more rapidly at higher temperatures, owing to the increased atomic mobility. Thus the longer the time at any given temperature in the austenitic range, the greater will be the amount of carbide and alloying elements (if present) taken into solution, the more homogeneous the austenite due to diffusion of these dissolving elements and the larger the austenitic grain size—all within limits fixed by the equilibrium conditions of these reactions at the particular temperature under consideration. Carbide particles, in particular, require a surprisingly long time interval for complete solution even when the temperature is such as to cause their ultimate solution, that is, above A_{cm} .

Since the constitutional changes which we aim to bring about at the maximum temperature are comparatively rapid, the element of time is less important than the actual temperature itself. In general, a relatively small increase in temperature will have a far greater effect in accomplishing the desired change than a longer time at some lower temperature; this is particularly true for the diffusion and grain growth changes mentioned above. On the other hand, when we consider the question of time at temperature from the standpoint of thickness of section, thermal conductivity of the metal, scaling, decarburization and other surface reactions dependent upon furnace atmosphere, the time factor assumes greater significance. The heavier the section or the lower its thermal conductivity, the longer the time necessary to attain uniform temperature throughout the piece; in the great majority of cases, uniformity of temperature throughout the piece is highly essential. Scaling, decarburization and similar surface phenomena all proceed continuously with time at temperature and if these effects prove to be detrimental it behooves the heat treater to keep the time as short as possible. Many of these surface reactions can be limited or even advantageously utilized by proper adjustment of the furnace atmosphere as, for example, when we intentionally introduce elements into steel by means of carburizing, nitriding, or a similar treatment.

In general, the time at maximum temperature should be long enough to attain uniformity of temperature and to bring about the desired constitutional changes; it frequently happens that these two aims can be accomplished in about the same time. On the other hand, the time at temperature should be kept to the minimum consistent with the above requirements in order to avoid undesirable effects from austenitic grain growth or surface changes due to the heating atmosphere.

Cooling—When the steel has attained the predetermined temperature throughout, the next step is to cool it at the proper rate to develop the desired structure. When, for a given steel, the austenite on cooling transforms to an aggregate of ferrite and carbide, or to martensite, the resultant structure—hence the mechanical properties—is, to a large extent, determined by the temperature at which this transformation actually takes place. With a slow cooling rate only moderate undercooling occurs; the transformation takes place just slightly below the lower critical temperature (A_1), and the resulting structure is characterized by coarse, lamellar pearlite of relatively low strength and hardness and high ductility. With such a slow cooling, there is, in addition to the pearlite reaction, a precipitation of proeutec-

toid ferrite in hypoeutectoid steels and of proeutectoid carbide in hypereutectoid steels; these proeutectoid constituents usually precipitate in the austenite grain boundaries and thus outline the austenite grains which existed at the maximum temperature; advantage is taken of this behavior in making austenite grain size measurements in hypo and hypereutectoid steels.

With progressively greater rates of cooling the actual temperature of transformation is progressively lowered by undercooling until, eventually, it is depressed to temperatures in the vicinity of 950-1000°F.; the lamellar pearlite becomes progressively finer, stronger, harder and less ductile, and the precipitation of the proeutectoid phases—ferrite or carbide, as the case may be—gradually diminishes in volume until finally at the faster cooling rates, it may be suppressed altogether. However, in the very low-carbon steels (0.20% carbon and lower) there is so much excess ferrite available that its precipitation ordinarily cannot be suppressed even with the most drastic cooling.

If the cooling speed is increased still further, as in quenching, the transformation is depressed by undercooling to temperatures approaching room temperature; the product of the austenite transformation at these low temperatures is not pearlite, but martensite, the characteristic constituent of fully hardened steel. The cooling rate which just causes the steel to harden fully to the martensitic condition is known as the "critical cooling speed"; it depends upon the composition and the austenite grain size of the steel. Martensite is now generally considered to be an unstable, supersaturated solid solution of carbon in alpha iron; it is glass-hard, brittle, and in steels carrying more than about 0.5% carbon, always in a condition of high internal stress, due, in part, to the volume changes accompanying the gamma to alpha transformation, to the solid solution effect, and to the drastic cooling which the material underwent in the hardening operation. In this condition steel is ready to precipitate its carbon and to relieve itself of stresses at the first opportunity, as, for example, on reheating for tempering or drawing-back. In some cases, fully hardened steel may relieve itself of internal stresses by spontaneous cracking, a fact well known to practical heat treaters.

At cooling rates intermediate between those giving rise to the pearlitic structures and those yielding martensite, mixtures of the two structures may be formed due to part of the transformation occurring at the higher temperatures and part at the lower; this mixed structure is always encountered in the transition zone between the hardened exterior and unhardened core of quenched heavy sections in which the surface may have cooled fast enough to form martensite while the interior cooled more slowly and transformed to the softer pearlitic products at higher temperature. Thus it is evident that thickness of section has a marked influence on the depth to which a given steel may be hardened (hardenability) at any particular cooling rate.

Effect of Alloys—The mechanism by which, at any particular cooling rate, dissolved alloy content depresses the transformation to lower temperatures as compared to carbon steel, is now fairly well understood. The action is due to the retarding of the fundamental transformation rate of the alloy bearing austenite, causing the finer, harder pearlitic structures to be formed at any given slow cooling rate or resulting in deeper hardening characteristics on rapid cooling—all, of course, as compared to plain carbon steels. Thus it corresponds to a faster cooling rate prior to the beginning of transformation as compared to carbon steel. A so-called "air hardening" steel, therefore, is one in which the transformation rate has been so retarded by the addition of alloys as to form fully hard martensite even on moderately slow cooling from the austenitic condition. In high alloy steels containing substantial amounts of the austenite-stabilizing elements the austenite solid solution may be retained all the way down to room temperature by the use of even very moderate cooling rates such as air cooling; these steels constitute extreme examples of the retarding of the fundamental transformation rate by the addition of alloying elements.

Effect of Austenite Grain Size—Increasing the austenite grain size by employing higher maximum temperatures before cooling has an effect upon hardenability similar to that of adding alloys; coarsening the austenite grain retards the fundamental transformation rate and results in harder, finer pearlitic structures, or deeper hardening characteristics, for any given rate of cooling as compared to the same steel in the fine grained condition.

Effect of Thickness of Section—The influence of size of section must be taken into account in any consideration of the subject of heat treatment from the stand-

point of cooling rate. A heavy section cannot be cooled as rapidly as a thin section; the interior of a heavy section cooling more slowly than the surface, transforms not only at a later time, but at a higher temperature and hence to a softer product than the more rapidly cooling exterior. This gives rise to differences in properties between the interior and exterior as well as to possible distortion, nonuniform internal stress and other difficulties well known to those familiar with heat treating practice; the subject is discussed more fully elsewhere in this volume, page 512.

Effect of Condition of Surface—Another factor which may be mentioned in connection with cooling practices is that of the surface condition of the metal about to be cooled. Steel which carries a heavy insulating coating of scale from the heating operation cannot be cooled as rapidly, under a given set of cooling conditions, as steel which is free from scale. This may result in erratic and non-uniform properties in the final product, particularly in connection with treatments designed to achieve full hardening; soft spots, or in extreme cases, complete lack of hardening may result from attempts to quench badly scaled steel. The remedy, of course, is either to descale in some manner before cooling, or practically, to carry out the heating operation in a less severely scaling atmosphere. Decarburization may cause nonuniform hardening and other undesirable effects, particularly as reflected in the behavior of the material under repeated or alternating stress (fatigue).

To summarize the effect of cooling rate on a given steel, the slower rate yields the softer pearlitic structures while the rapid rate gives rise to the harder, martensitic structures; the former are relatively stable and stress-free while the latter are quite unstable and are likely to be so highly stressed internally as to be unserviceable for most purposes. This brings us to the question of whether the heat treatment is to be considered as completed at the end of the cooling operation or whether a further treatment is necessary. Ordinarily, the softer, pearlitic products resulting from the slow cooling operations require no further treatment since they are relatively stable (although not entirely so) from a structural standpoint. Occasionally, the fine, pearlitic structures are given a low temperature (subcritical) stress relieving anneal; such a treatment tends to spheroidize the fine lamellar carbides, the extent of spheroidization depending upon the temperature and time of the annealing operation. On the other hand, the harder, martensitic products, resulting from rapid cooling or quenching, are usually so unstable and brittle as to be of little practical value in the "as quenched" condition; hence a further treatment known as *tempering* is almost invariably applied.

Tempering—Tempering of fully hardened steel is carried out for relief of quenching stresses and for the recovery of a limited degree of toughness and ductility. The operation consists of heating at temperatures below the lower transformation or critical temperature (A_1), that is, at temperatures at which the steel is in the ferritic condition. The stress relief and recovery of ductility are brought about through precipitation of carbide from the supersaturated, unstable alpha iron solid solution (martensite) and through diffusion and coalescence of the carbide as the tempering operation proceeds.

It should be clearly understood that the carbide precipitation which occurs during the tempering of martensite does not take the form of plates or lamellae characteristic of the pearlitic structures formed directly out of austenite on slow cooling; on the contrary, the carbide precipitated during tempering takes the form of a fine dispersion of more or less spheroidal particles, the size of which depends upon the time-temperature conditions of the tempering operation; this cannot be emphasized too strongly since there appears to be considerable confusion on this particular point. So far as is known, no one has ever succeeded in making lamellar pearlite out of martensite by a subcritical tempering treatment. The tensile properties of a tempered specimen (spheroidal carbides) and a pearlitic specimen (lamellar carbides) of the same steel, at the same hardness, are distinctly different.

The higher the tempering temperature, or the longer the time at temperature, the coarser the spheroidal carbide particles and the softer and more ductile the steel. Alloy steels containing the carbide forming elements tend to show greater resistance to softening in tempering than plain carbon steels; hence higher temperatures or longer times may be employed in tempering such steels, thereby attaining more thorough relief of quenching stresses without proportionate sacrifice in hardness.

Some steels are susceptible to embrittlement, or at least a reduction in ductility,

when tempered in the so-called "blue heat" range, or when slowly cooled through this range after tempering. This, which is due presumably to some precipitation in the steel, can be minimized either by tempering at temperatures below the range in which the steel is sensitive, or by rapid cooling through the range if the tempering temperature is above it.

In general then, the tempering operation may be conducted so as to give almost any desired combination of properties by proper selection of the time-temperature conditions. The correct time-temperature cycle for any given set of properties depends, to a large extent, upon the composition of the steel, and particularly the composition of the austenite with respect to its dissolved carbon and alloy content prior to its conversion to martensite by rapid cooling.

Flame Hardening*

General—The "flame hardening" process, also known as the "Shorter" process or "Shorterizing," embraces the use of the oxy-acetylene flame to raise the temperature of the surface of ferrous material above the Ac₁ transformation point so that subsequent quenching will produce a desired hardness and structure.

The hardened layer varies in depth from a mere skin to $\frac{1}{4}$ in., according to the operating practice and type of material being treated. This method forms a hardened case on the surface of the parts being treated without altering the chemical composition, so must not be confused with such processes as carburizing, cyaniding, or nitriding that require the addition or absorption of other elements.

Comparison of Furnace and Flame Hardening—For mass heat treating of small objects which are to be uniformly hardened the furnace method is usually the most efficient and economical. There are many instances where the parts are too large or where there is danger of excessive distortion when using the furnace method. In such cases, the oxy-acetylene flame may be used to advantage since this process permits the hardening of any accessible portion of an article with negligible distortion.

Distortion—While flame hardening tends to minimize distortion, there are applications which must be held to little or practically no distortion. The amount of warp is not predictable and frequently it is not possible to prophesy the direction of distortion. The composition of the material, its physical condition, the depth and degree of hardness, and the section undergoing treatment should be considered. Practically, the answer must be determined by experiment on the particular section. Distortion is greatest when only one side of a thin object is heated and quenched. Often it will be found that some simple expedient such as a water bath or compensative heating on the opposite side from which the flame hardening is being done will hold distortion to a minimum. In sections where both sides of an object are hardened simultaneously, such as gear teeth, distortion is practically nil. Where the metal section between the bore and root diameter is less than $1\frac{1}{2}$ in., the bore may expand several thousandths.

Materials—Steels—To obtain any appreciable degree of hardening, the material treated must be of such a chemical composition as to readily respond to heating and quenching. For carbon steels the carbon content should be at least 0.35%; the best range is 0.40-0.70%. Steels with a higher carbon content may be successfully flame hardened, but greater care has to be exercised to prevent surface checking or cracking.

The high alloy steels produce a more difficult problem in heating and quenching, and many are to be avoided. Table I illustrates the type of steels that have been successfully flame hardened.

Table I
Types of Steels Suitable for Flame Hardening*

(See page 612 for compositions)

S.A.E. Carbon Steels	S.A.E. Manganese Steels	S.A.E. Nickel Steels	S.A.E. Nickel-Chromium Steels	S.A.E. Chromium Steels	S.A.E. Chromium-Vanadium Steels	S.A.E. Molybdenum Steels	Miscellaneous Materials
1035	T1330	2330	3140	5140	6135	4130	Carbon Vanadium steels
1040	T1335	2335	X3140	52100	6140	X4130	
X1040	T1340	2340	3145			4135	Carbon Molybdenum steels
1045	T1345	2345	3230			4140	
X1045		2350	3240			4340	Malleable iron
1050			3335			4640	Cast iron
X1050			3340				Graphitic steel
1055			3435				
X1055							
1060							
1095							

*As a guide to the type of steels, the S.A.E. steels are listed but many other steels similar to these grades are also flame hardened.

*Prepared by the Subcommittee on Flame Hardening. The membership of the subcommittee

Cast Iron—Pearlitic cast irons and malleable irons offer a broad field for the flame hardening process. Chilled, cast iron has a high resistance to wear, but ordinary chilled castings can not be used when machined surfaces are required and where dimensional accuracy is important. It is here that flame hardening is particularly useful, because the wearing properties of cast iron surfaces are greatly increased by this process. Table II shows the results obtained in flame hardening a number of cast irons.

Properties—This method of heat treatment produces the optimum hardness on the surfaces subjected to wear, but leaves the core in its original condition. This makes it possible to heat treat the core to the desired properties and then impart a hard surface layer without altering the core.



"A" case of gray iron immediately below treated surface, 500X.
"B" untreated base metal, 500X.

Table II
Brinell Hardness of Cast Iron Before and After Flame Hardening

Combined Carbon	Graphitic Carbon	Silicon	Nickel	Chromium	Brinell Hardness, 3,000 kg. load	
					Before Hardening	After Hardening
0.49	2.61	1.91	...	0.064	235	450
0.49	2.58	1.92	...	0.064	241	472
0.96	1.92	1.42	trace	0.11	350	560
0.76	2.35	2.43	...	0.022	223	441
0.74	2.00	2.26	0.48	0.36	269	450
0.69	2.08	1.82	0.16	0.10	253	472
2.09	0.56	1.01	...	0.24	387	578
0.64	2.30	1.58	0.07	0.076	292	450

Hardness—The surface hardness that can be anticipated from flame hardening any of the steels tabulated in Table I at least equals the same as would be obtained from these analysis if hardened in a conventional heat treating furnace and quenched. Table III gives hardness values for a guide as to what may be obtained.

The hardness is maintained through about 80% of the depth of the hardened area. The core is not affected and there is no rapid falling off of the hardness, the transition from case to core being gradual (Fig. 1). As a sharp line of demarcation between the case and core is not observed flaking and spalling under service stresses are avoided.

Application and Methods—This process may be adapted to castings, forgings, or rolled sections. Size is not a limiting factor and if the part is fabricated from material of the proper analysis and the sections which require hardening are readily accessible, then the part may be flame hardened.

Flat sections, circular parts, irregular shapes and varied combinations may be successfully hardened by this method.

The Stationary or Spot Hardening Method—This method includes operations where the torch and work are stationary during the treatment.

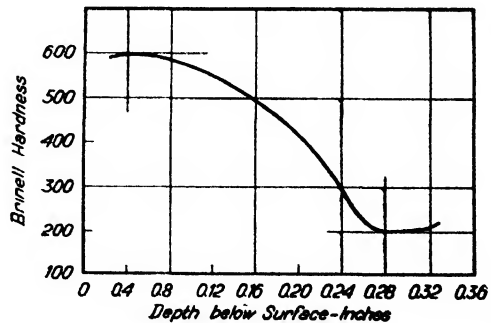
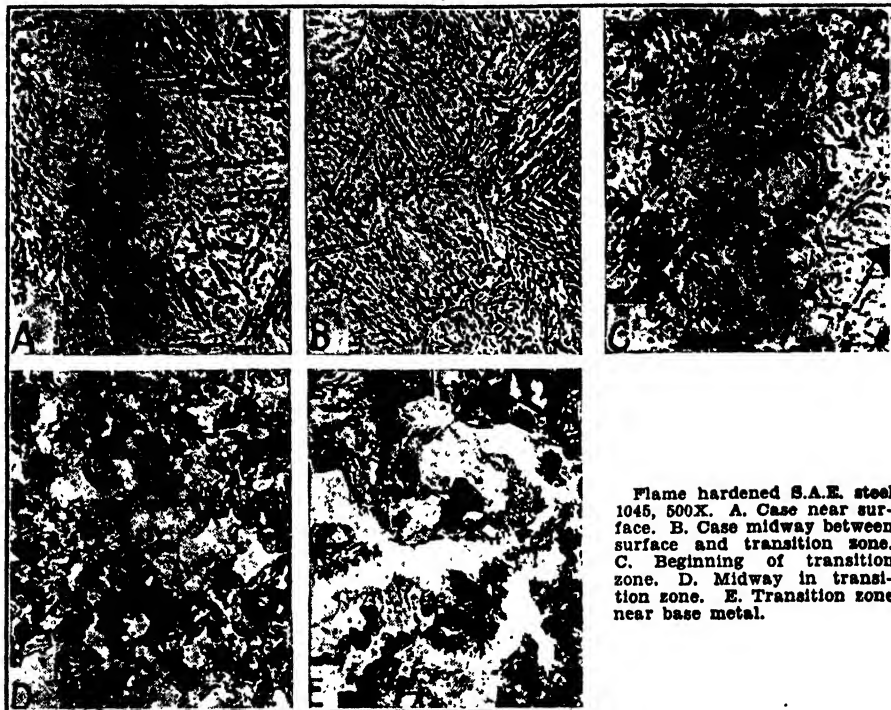


Fig. 1—Hardness exploration of flame hardened case on S.A.E. 1045 steel.

Straight Line Progressive Method—In this method, the torch and quench travel along the face of the object such as gear teeth or track rails. With this procedure only the material directly under the heating head is undergoing treatment at any instant.

Rotary Progressive—In this method, cylindrical objects of large diameter are rotated at a speed of from 3-12 in. per min. in front of a stationary flame. The torch being mounted so that it progressively heats and quenches the desired width of path to be hardened. This method leaves at the starting and stopping points a



Flame hardened S.A.E. steel 1045, 500X. A. Case near surface. B. Case midway between surface and transition zone. C. Beginning of transition zone. D. Midway in transition zone. E. Transition zone near base metal.

Table III
Expectant Hardness After Flame Hardening—Water Quenched

S.A.E. Steels	Scler.	Brinell	Rockwell C	S.A.E. Steels	Scler.	Brinell	Rockwell C
1035	37	350	25	3140	65	477	49
1040	63	461	47	3145	67	495	50
1045	70	514	52	3340*	84	627	60
1050	78	578	57	3435*	72	534	53
1060	84	627	60	4130	70	514	52
T1335	61	444	46	4140	81	601	58
T1340	65	477	49	4640*	84	627	60
T1345*	70	514	52	5140	81	601	58
2330	59	429	45	52100*	95	712	66
2335	61	444	46	6140	85	627	60

*These steels are recommended to be hardened by the spinning method only.

narrow oblique path which is generally two or three points softer on the Rockwell than the adjacent hardened areas. The tempering of the hardness at the overlap may be held to a minimum by placing an auxiliary cooling stream ahead of the torch.

Large cylindrical pieces may be hardened by mounting the torch in the tool post of a lathe and moving the carriage slowly along the cylinder axis, producing a spiral path, the width of the strip depending on the width of the torch. Where complete hardening is desired the paths should overlap about $\frac{1}{4}$ in.

Spinning Method—For hardening gears under 4 diametrical pitch and producing hardened bands on cylindrical surfaces of small diameter, the spinning method is employed using a water cooled tip without quenching jets. The heating flames cover the entire width of the path being hardened while the object is rotated rapidly (at a surface speed of approximately 100 r.p.m.). When the surface of the object has been heated to the desired temperature, the flames are extinguished, and the part is ejected or dropped into a tank of quenching medium or a spray quench is directed upon it. Where larger diameter surfaces are to be hardened it may be necessary to use two or more heating tips spaced equally around the cylinder circumference.

Progressive Spinning—This method may be employed for the hardening of cylindrical surfaces of extended length by progressing a heated band followed by a quenching stream along the axis of the cylinder being heated at the general progressive hardening speed of 3-12 in. per min. The work is mounted on centers and rotated at a speed of about 100 r.p.m. One or more torches, depending upon the diameter of the object, are mounted with the quenching arrangement on a separate carriage and are spaced at equal intervals along the objects perimeter so as to heat a narrow band. Moving the carriage slowly, the heated band is progressed along the axis of the cylinder followed by the quenching stream.

Hardening Irregular Surfaces—Irregular contours may be hardened by using specially designed torches. In many instances it is preferable to divide an irregular shape into several sections and treat each part as a separate operation. This method permits simplification of torch design as well as promoting easy operation, but it has the disadvantage that in certain applications or design, there may be produced zones of lower hardness at the junctions of the different sections.

Equipment—While there are instances where torch hardening must be performed by hand, most all operations may be mechanized and in order to reduce cost and obtain consistently uniform results, mechanical means should be used.

There are several types of flame hardening machines used in the United States, the Monitor, Radiograph, Sykes machine, the Gleason design, the Universal type, camshaft and rail hardening machines. Variable speeds of travel on all types of machines permit uniform treating of sections of different sizes and varying cross sections.

Torches—The recent developments of dependable internally water cooled torches and multiflame tips, capable of maintaining stable flames under severe heating conditions, in close proximity to the heated surface, and the operation of these tips by mechanical means have made possible the application of the flame hardening process to industrial production.

Tips—A large selection of flame hardening tips for hardening gear teeth, flat, round, and cylindrical surfaces; both internal and external are available. In general, for progressive hardening, the tips have integral water quenching jets at the proper distance to the rear of the heating flames, which progressively quench the surface as it is heated. The water jets perform two functions, that of cooling the tip, as well as quenching the heated surface. For other applications where the surface is first heated and then quenched separately, the tips are designed with internal cooling while an auxiliary quenching stream is used for quenching after the heating flames have been extinguished. These quenching streams may be built into the tip or may be separate.

Gear Hardening—In gear hardening the head is designed to allow operation in the restricted area between the teeth. Although it has been the practice until quite recently to flame harden the opposite sides of each tooth separately, the development of the "straddle type" heads has made simultaneous treatment possible.

With this method the gear may be hardened in half the time formerly required. In addition to time saving, the simultaneous application by the straddle method leaves both sides of the tooth hardened uniformly. As the straddle method provides for heat and quench striking both sides of the tooth simultaneously, the tendency for small teeth to distort is overcome.

To insure equal hardness and contour on each side of the tooth, the distance from tooth faces to head faces must be equal, and the flame intensities and gas



Section of flame hardened gear tooth showing case.

ratios the same. The leading flames of the heads must arrive at the entering end of the tooth at the same time.

Quenching pressures are important, especially on the small tooth sizes. Too much pressure will interfere with the flames, and too little pressure may not produce sufficient hardness.

Stress Relieving—Tempering or stress relieving is absolutely essential and should follow shortly after quenching. This operation is performed in a standard type heat treating furnace or air or oil bath at temperatures from 350-400°F. This low temperature is sufficient to relieve the stresses set up by quenching, but has little if any effect on the hardness. After this tempering operation the work may be removed from the furnace and cooled in still air or may be furnace cooled.

Economics—Computation of cost and gas consumption per unit area depends upon several varying factors, such as set up time, case depth, method used, rate of torch travel, size of tip, and relation of the surface to mass of the object treated. It would appear that owing to these variables only an approximation can be made. A fair estimating figure is that $\frac{1}{4}$ cu. ft. of each gas will flame harden one sq. in. of surface to a depth of about $\frac{1}{8}$ in. In certain practices this figure has been reduced to $\frac{1}{8}$ cu. ft. of each gas per sq. in. of surface treated; speed range 3-10 in. per minute.

Precautions—While this method of hardening appears simple, there exist a number of variables which have to be carefully regulated and co-ordinated to insure the most satisfactory results.

Since flame hardening is only surface hardening and only a comparatively thin layer is treated, it is of the utmost importance that this surface be in the proper condition to successfully respond to this operation. Decarburized zones are to be avoided. The components must have the requisite carbon content at the surface as well as underneath.

The surfaces to be hardened must be scale-free as scale retards the quench and maximum hardness will not be attained. Pits, blow holes, seams and laps, are to be avoided as they may result in the formation of large surface holes or develop into cracks during the quenching operation.

This method produces no scaling or pitting and the hardened surfaces are left clean and smooth but precaution must be taken, because a temperature of 6300°F. is applied at a distance of only $\frac{1}{4}$ in. from the surface desired to heat to a temperature range of only 1450-1550°F. Positioning the flame too close to the work, or applying it for too long a time, may result in searing or burning the surface material and producing a brittle and coarse underlying grain, or it may result in overhardening and surface checking.

The operator must learn to judge the proper quenching temperatures and while this varies with different steels, practice will soon permit him to judge with fair accuracy. The light of the flame makes the steel appear colder than the actual temperature and a new operator may overheat the work. Inexperienced operators often report that the material is excessively hot under the last two flames but cold in between, but with a properly designed head the heat will be distributed satisfactorily although the appearance under the flame would tend to indicate otherwise.

Heat Treatment of Carbon Steels*

General—This article covers the heat treatments for carbon steels of all commonly used types except those classified as tool steels. All common applications are covered except those of case hardening, spring making and the hardening of tools. From the treatments not covered, see appropriate sections of this Handbook.

Chemical Composition—The composition of the steels covered are the S.A.E. specifications for carbon steels as given on page 612.

Heat Treatment—General—Table I gives the commonly used temperatures and quenching media for heat treating some of the carbon steels. The S.A.E. carbon steels whose treatments are representative of a particular carbon range are the only steels listed in Table I. For a discussion of the principles involved, the reader is referred to the articles "Heat Treatment of Metals" and "Principles of the Heat Treatment of Iron and Steel" given in this Handbook.

Table I
Heat Treatments for Carbon Steels

S.A.E. No.	Normalize, °F.	Anneal, °F.	Quench, °F.	Quenching Medium
1010	1650-1800	1600-1700 or 1000-1350 ¹	1650-1700	Water ³ -Oil ^{4,5}
1020	1650-1750	1600-1700 or 1000-1350 ¹	1575-1675	Water ³ -Oil ^{4,5}
1030	1600-1675	1575-1650 or 1250-1400 ²	1550-1625	Water ³ -Oil
1035	1575-1650	1575-1625 or 1250-1400 ²	1525-1600	Water ³ -Oil
1040	1575-1650	1550-1600	1500-1575	Water ³ -Oil
1045	1550-1650	1550-1600	1475-1550	Water ³ -Oil
1050	1550-1625	1550-1600	1450-1525	Water ³ -Oil
1060	1525-1600	1500-1575	1425-1550	Water ³ -Oil
1070	1500-1575	1475-1550	1425-1550	Water ³ -Oil
1080	1500-1575	1475-1550 or 1250-1400 ²	1400-1525	Water ³ -Oil
1095	1500-1575	1475-1550 or 1250-1400 ²	1400-1525	Water ³ -Oil

¹For explanation of double temperature range, see discussion of Group I. ²This temperature range is for spheroidizing. ³Brine or caustic soda solution is frequently used. ⁴Soluble oil solution is used for hardening bolts. ⁵Mineral oil is used when treating for machinability only.

To simplify further discussion of the treatment, the steels will be classified as follows: Group I, S.A.E. 1010-1025; Group II, S.A.E. 1030-1050; Group III, S.A.E. 1055-1095.

Group I, S.A.E. Steels 1010-1025—There are three important kinds of heat treatment used on these low carbon steels: (1) Process treating of material to prepare it for subsequent operations; (2) treatment of finished parts to improve physical properties, and (3) case hardening, which is covered elsewhere in this Handbook, so does not concern this article.

The process treatment of these steels is applied principally to sheet and strip for stamping and drawing and to parts made from such steels between drawing operations.

It is often necessary to process anneal drawn products between operations to relieve work strain in order to permit further working. This operation is usually carried out at temperatures between the recrystallization temperature, and the lower critical temperature. Its effect is to soften by recrystallization and grain growth of ferrite. It is desirable to keep the recrystallized grain size relatively fine and for that reason rapid heating and short holding time at temperature are desirable. The low temperatures also keep the scaling at a minimum. The customary practice is to discharge the parts from the temperature into air. If complete surface protection is desired, the material may be heated in liquid baths or controlled atmosphere furnaces.

A similar practice may be used in the treatment of low carbon cold headed bolts. Sometimes the strains introduced from cold working so weaken the heads that they break through the most severely worked portion at the slightest disturbance. Process annealing as described above is sometimes used to overcome this condition. The temperatures used are, as a rule, close to the lower critical. This results in considerable reduction of the normal cold drawn physical properties. A stress relieving treatment at about 1000°F. for cold headed bolts made from S.A.E. 1020 for the automotive industry retains much of the strength acquired in cold

*Prepared by the Subcommittee on the Heat Treatment of Carbon Steels. The membership was as follows: M. L. Frey, Chairman; E. O. Dixon, and T. A. Benton.

working and provides ample toughness. A more common practice is to combine a stress relieving treatment with an actual quench from the upper critical temperature or slightly above. This treatment produces physical properties which approach those of the cold drawn stock. A common quenching medium is a water solution of soluble oil. Its use produces two desirable results. First, the surface of the parts is given a pleasing black color which is accepted as a commercial finish and, second, the speed of the quench is slowed down to the point where extreme hardness is not produced and it is not necessary to temper the parts.

The heat treatment applied to machinery parts other than bolts and stampings sometimes consists of normalizing when high toughness is desired. Since the air hardening properties of these steels are low, the resulting tensile strength and yield point will be low. Annealing from above the upper critical temperature, followed by slow cooling is seldom used because it results in low strength and poor machinability. With special work, a drastic quenching as in water or 5% caustic followed by tempering is used to produce moderate strength and high toughness in parts of small section. The obtainable increase in strength, however, is not sufficient for general practice, so it is better to use a material with higher carbon steel or alloy steel.

Heat treatments to improve machinability are frequently employed. The generally poor machinability of the low carbon steels, except those containing sulphur or other special alloying elements, is due principally to the fact that the proportion of free ferrite to carbide is high. Additional factors are the form in which the carbide occurs and the distribution pattern of the carbide containing constituent. Because it is soft and ductile, ferrite is responsible for the tearing action of tools and the loading of metal on their cutting edges. Any treatment which distributes the carbide throughout the ferrite mass in such a way as to effectively break it up favors machinability. In the case of spheroidized steels, the distribution of free ferrite and carbide is the highest possible, and in this condition the machinability is poor in spite of a favorable distribution pattern. In fully annealed steels the distribution of free ferrite and carbide is more favorable because the carbide is present as pearlite, which occupies more volume, but the distribution pattern is poor. Normalizing improves this condition and therefore aids machining. Even though the as-forged structure varies considerably, the distribution pattern is usually good and steels in this condition machine with reasonable satisfaction.

The best machinability in steels up to 0.20% carbon is usually obtained by quenching the steel into mineral oil from 1500-1600°F. Since the rate of cooling is below the critical cooling rate, no martensite is formed and tempering is not required (with the exception of steels 1025 and X1025). This treatment improves machinability by improving the distribution pattern for ferrite and carbides.

Group II, S.A.E. Steels 1030-1050—Because of their higher carbon content, heat treating becomes of increasing importance when considering steels of this group. They are the most versatile of the carbon steels because their hardenability can be varied over a wide range by suitable control of the various factors.

Hardenability is an inverse function of the critical cooling rate¹; that is, a low critical rate produces high hardenability and a high one, low hardenability. The critical cooling rate may be defined as that rate of cooling through the transformation range which must be equalled or exceeded if complete hardening (martensitization) is to take place. A knowledge of the factors affecting this critical cooling rate may, therefore, be used to clarify the matter of hardenability. The relationships have not been fully defined quantitatively and the following discussion is in qualitative terms. In addition to those factors affecting the critical cooling rate, other pertinent points are presented.

1. Increasing the carbon content to the eutectoid point lowers moderately the critical cooling rate² but since we are primarily interested in controlling the hardenability of a steel with a narrow range of carbon, this factor is of secondary importance. The primary factor is that carbon alone up to about 0.55% determines the surface hardness obtainable,³ provided first, that all carbon is in solution in the austenite at the time of quenching, second that the critical cooling rate is reached or exceeded in quenching and, third that no appreciable austenite is retained after the quench. This statement applies regardless of the presence of other alloying elements. Maximum hardness is attained at about 0.55% carbon and further increase has no effect on surface hardness.

2. The effect of manganese, silicon and other alloying elements is to decrease the critical cooling rate,² thus making easier the attainment of full hardness as determined by the carbon and increasing the depth to which hardening will take

place in any particular section. In the carbon steels under consideration, manganese and silicon in moderate amounts are the principal hardening elements to be considered. Their effect is appreciable but not nearly as pronounced as the larger quantities found in some alloy steels.

3. Hardenability decreases as grain size number increases^{7, 10}; that is, fine grained steels harden less deeply than coarse grained steels.^{3, 4} It has been shown⁴ that fine grained steels have a higher critical cooling rate than coarse grained steels; therefore, any alloying element which reduces this rate will tend to offset the effect of fine grain. In the carbon steels manganese is frequently used for this purpose.

4. Normal steels harden more deeply than abnormal steels because of their lower critical cooling rate. Contrary to popular opinion, abnormality is not confined to fine grained steels. Both manganese and silicon are effective in counteracting abnormality.

5. Hardenability decreases as size of section increases.⁸ This effect takes place in two stages; first, there is a reduction in depth of hardening with little or no reduction of surface hardness; second, with further increase of size there is a marked reduction in surface hardness until finally no worthwhile hardening can be observed.

6. Depth of hardening increases as quenching temperature is increased from the upper critical point of the steel to a point well above commercial hardening temperatures. This effect is caused by the fact that increasing the temperature from which the piece is quenched increases the grain size and effective cooling speed of the quench. Surface hardness falls off slightly with increase of temperature after the grain coarsening temperature is reached.

7. Depth hardness increases as the severity (speed) of the quench increases up to the critical cooling rate. When that rate has been reached, there will be no further increase in surface hardness since this value is controlled solely by carbon content. Further increase in severity of quench may or may not result in increased depth of hardening, depending on the effect of other factors, principally manganese, silicon and grain size. It follows that the depth hardness of fine grained steels will be increased by increasing the severity of the quench and, conversely, the depth hardness of coarse grained steels will be decreased by decreasing the severity of the quench. It should also be kept in mind that increasing the speed of quenching beyond that necessary to produce the required hardness is usually of little value and often results in warpage and breakage.

8. The rate of heat removal in quenching is seriously affected by the surface condition of the work. Tightly adhering or heavy scale or soot or tightly adhering material from liquid baths prevent rapid transfer of heat to the quench, thus making more difficult and sometimes impossible the attainment of critical cooling speed and full surface hardness.

9. The rate of heating of parts for quenching has a marked effect on hardenability under certain conditions. In those cases where the structure is nonuniform as from severe banding or lack of proper normalizing or annealing, extremely rapid heating such as may be obtained in liquid baths will not allow sufficient time for diffusion of carbon and other alloying elements in the austenite with the result that nonuniform or low hardness will be produced. In the case of steels containing free carbides, for example, spheroidized material, sufficient time must be allowed for the solution of these carbides, otherwise the austenite at the time of quenching will have a lower carbon content than is represented by the chemical composition of the material and disappointing results may be obtained. For a case in which this condition is deliberately produced see the discussion under Group III.

10. From the above, it is evident that structure of the material prior to hardening has an important bearing on the hardenability.

For best physical properties after hardening and tempering, these steels should be either normalized or annealed before hardening. Parts made from bar stock are frequently not given any treatment prior to hardening but it is common practice to so treat forgings. Heating practice for these steels should be in accordance with the principle^{11, 12} given elsewhere.

Like the low carbon steels of Group I, these steels machine poorly in the spheroidized state. This may be improved, especially in the case of fine grained steels, by high normalizing temperatures such as the upper limits of the ranges in Table I. This high temperature treatment temporarily coarsens the grain, thus improving machinability. Upon subsequent treating the coarsening effect disappears and the steels again behave as fine grained materials.

Cold headed products are commonly made from these steels, especially those of lower carbon. Process treating before cold working is usually necessary because the higher carbon decreases the workability. In some cases normalizing or annealing above the upper critical is used but more frequently a spheroidizing treatment is used. The degree of spheroidization required will depend upon the application. After the mechanical operations are finished, the parts are heat treated by quenching and tempering.

These steels are widely used for machinery parts for moderate duty. When such parts are to be machined after heat treatment, the maximum hardness is usually held below 300 Brinell and is frequently much lower. When no machining except grinding is required hardnesses may go much higher.

The following gives the range within which the hardness of representative parts is usually found:

Name or Part	Grade of Steel	Brinell Hardness No.
Crankshafts	1040, 1045	228-286
Connecting Rods	1035, 1040	187-241
Wheel Flanges	1030, 1035	302-444
Steering Arms	1035, 1040	207-269
Shafts	1045, 1050	228-402
Front Axles	1035, 1040	196-269
Couplings	1030, 1045	207-321
Thrust Washers	1040, 1045	341-514
Wheel Lugs	1040, 1045	364-477

The selection of a quenching medium will vary with the steel composition, the design of the part, the hardenability of the steel and the hardness desired in the finished part. When the design of the part permits, the best combination of strength and toughness results from full hardening (martensitization) of the part followed by suitable tempering. In these steels this nearly always means water, brine or caustic soda quenching. Often the design is such that breakage will result from such quenching or the distortion limits will be exceeded and the mild oil quench, with its lower hardness and less complete retention of ferrite must be used. Considerable help may be had in such cases, from proper adjustment of chemical composition and from control of hardenability. The lower carbon steels, if fine grained and abnormal, are shallow hardening even when quenched in caustic while the higher carbon steels when coarse grained and normal, will give hardnesses of 450 Brinell when oil quenched in small sections and exhibit satisfactory hardening up to two in. dia. The wide range shown in the quenching temperatures in Table I is made necessary by the fact that a wide range of conditions must be met. It is not intended that such a temperature range should be used on any one part or under any given set of conditions. General practise is to use a suitable temperature within $\pm 10^{\circ}\text{F}$. The lower temperatures should be used for the X1300 series (high manganese) steels, light sections, coarse grained material or water quenching. Conversely the 1000 series (carbon) steels, heavy sections, fine grained material and oil quenching will require the higher temperatures.

A type of treatment finding considerable use is the light case hardening of many machinery parts. The material is heated to its normal hardening temperature in an activated bath and quenched into oil. The purpose of this treatment is to produce a superficial hard skin for wear resistance. Only low temperature tempering can be done on such parts, otherwise the surface hardness will be impaired. It is necessary to choose the degree of hardenability in relation to section such that the required degree of toughness is obtained in the as-quenched product. In applying such parts it must be borne in mind that the presence of the hard skin reduces their notch toughness below that which would be found if the skin were absent.

Many common hand tools such as pliers, open end wrenches, screw drivers and a few edged tools such as tin snips and brush knives are made from these steels. The cutting tools are necessarily water, brine or caustic quenched locally on the cutting edges, followed by suitable tempering treatments. In some cases the edge is time quenched severely, followed by oil quenching the remainder of the tool for partial strengthening. Pliers, wrenches and screw drivers, when made of these grades are usually quenched in water and suitably tempered. The quenching may be either local or complete.

Group III, S.A.E. Steels 1055-1095—The principal uses of steels of this group are heavy machinery parts, hand tools, cutting tools, and springs. The material and heat treatment for springs are covered elsewhere in this Handbook.

For heavy machinery parts such as shafts, collars and the like, steels S.A.E. X1055 and X1065 may be used either as normalized and tempered for moderate strengths or as quenched and tempered for higher strengths. Other steels in the list may be used but the combination of carbon and manganese in the two mentioned makes them particularly well adapted for such applications. In selecting any of these steels for such applications, it must be remembered that even with all hardenability factors favorable, these steels are essentially shallow hardening (as compared to alloy steels) because carbon alone, or in combination with manganese in the amounts involved here, does not promote deep hardening. Therefore, the sections for which such steels are suited will be definitely limited. In spite of this characteristic, the danger of breakage when treating such parts, especially when changes in section are involved is real and must be carefully guarded against.

Hand tools of many kinds such as open end wrenches, Stillson wrenches, hammers, mauls, pliers and screw drivers and cutting tools, both hand and power operated, such as hatchets, axes, mower knives and band knives, when made of carbon steels classed as commercial as opposed to tool grades, are made of steels in this group. The combination of carbon and manganese in the steels used may vary widely for the same type of tool, depending partly upon available equipment for manufacture and partly upon personal experience with or preference for certain combinations. In some cases, lower manganese content will be used. This is justified when it makes a particular carbon range easier to handle but it should be understood that in most cases a combination of lower carbon and higher manganese would serve just as well. An exception to this is the case of hand cutting tools which will be discussed later.

Forged parts should be either normalized or annealed, preferably the latter, first, because refinement of the forging structure is important in producing a first quality hardened product and, second, because the parts as they come from the hammer are too hard for cold trimming of the flash and for any machining operations. Ordinary annealing practice as given in the table, followed by furnace cooling to 1100°F. is satisfactory for most parts.

For hardening wrenches, except the Stillson type, screw drivers, pliers, and such tools, oil quenching, followed by tempering to the required hardness range is generally used. Even when no reduction of as-quenched hardness is desired, a stress relieving temper at 300-375°F. is desirable to prevent sudden service failures. In the case of Stillson type wrenches the jaw teeth are really cutting edges and are nearly always water or brine quenched to produce full hardness. The jaws may be either locally heated and quenched or the parts may be heated all over, the jaws locally time quenched for full hardness in water or brine and the entire part then quenched into oil for partial hardening of the remainder. In this way considerable structural strength is obtained.

Hammers must possess high hardness on the striking face and somewhat lower hardness on claws, if of that type. They are usually locally hardened and tempered on each end in accordance with their type. The striking face is always water or brine quenched. Satisfactory service depends upon getting the proper depth of fully hardened (martensitic) surface on this face, followed by a stress relieving temper at about 350°F.

Hand cutting tools, most particularly axes and hatchets, must possess high hardness and high relative toughness in their cutting edge as well as the ability to hold a keen edge. Since nothing is so effective as carbon in imparting the latter property, the carbon content is always higher than would be the case if hardness and toughness alone were to be considered. Many such tools are given an ordinary furnace anneal following forging, but in many cases they are prepared for hardening by spheroidization. This may be done as a separate operation following regular annealing but most frequently the refining and spheroidizing treatments are accomplished by quenching into oil from 1600°F. followed by tempering at 1250-1375°F. Heating for quenching puts all constituents into solid solution and quenching retains the carbon in a finely divided state from which condition spheroidization takes place rapidly at the temperatures specified. For hardening, such tools are usually heated in liquid baths to the lowest temperature at which the piece can be hardened and then brine quenched. The quick heating of the liquid bath plus the low temperature fails to put all of the spheroidal carbon into solution with the result that the cutting edge of the tool consists of martensite of lower carbon content than indicated by the chemical composition of the steel in which are embedded many particles of cementite. In this condition the tool is at its maximum toughness relative to its hardness and the embedded carbides promote long life of the cutting edge.

Agricultural implements make much use of the steels in this group. Braces, control rods, shafts and similar parts are often made of high carbon steels, untreated, in order to obtain increased strength at low cost. The principal heat treated parts are plow shares, moldboards, coulters, cultivator shovels, discs for harrows and plows, mower and binder knives, ledger plates and band knives. Those parts used for cutting or turning soil must have the ability to resist abrasion and be moderately tough. They are made from various combinations of carbon and manganese such that full hardening may be obtained. Frequently the cutting edges of plow shares and cultivator shovels are water or brine quenched to obtain high hardness. Plow shares, moldboards and cultivator shovels are often made from "soft center steel" which consists of a layer of dead soft material between two equally thick layers of high carbon steel. This material is rolled from specially cast composite ingots. Such parts are heat treated to produce high hardness in the outer layer, leaving the relatively soft interior layer to provide toughness. The final product is similar in physical properties to a case hardened part, in fact, these parts are sometimes case hardened.

The grass and grain cutting tools are usually made of S.A.E. 1090 or 1095 because of the effect of carbon in providing the desired long life edge. These parts are made from strip stock by blanking and no annealing is done except probably some process annealing by the rolling mills at or below the critical. Spheroidization is, therefore, only occasionally obtained. Hardening is done usually in continuous furnaces provided with fixtures that cause the pieces to be differentially heated on the cutting edges only. Upon discharge the parts are quenched all over in oil and tempered at a low temperature. Final hardness on the cutting edges is in the neighborhood of 55-60 Rockwell C.

In many applications of the steels in this group, hardenability is of considerable importance and must be adjusted to the needs of the individual case for best results. Heat treating tests on representative or critical sections are the most satisfactory method of determining hardenability.

A method of heat treating in which, instead of being quenched and tempered in the usual manner, the pieces are heated in the regular manner, put into a liquid bath maintained at an elevated temperature and allowed to transform there, is suitable for steels of approximately eutectoid composition. This method, which is covered by patents, is similar to the patenting of high carbon wire. It is particularly useful in producing a combination of high hardness and high toughness. At the present time it has been developed only to the point where it is suitable for light sections usually not over $\frac{3}{8}$ in. Since further discussion is beyond the scope of this article, it is suggested that those interested consult the original publications.^{4, 11, 12}

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Composition and Heat Treatment of Carbon and Alloy Steel Castings*

Heat Treatment for Carbon Steel Castings

General—The following article applies generally to commercial castings for ordinary construction purposes, and not for special uses. Where authoritative specifications, as for example A.S.T.M. specifications, exist, the practice listed conforms to such specifications.

Chemical Composition—The range of chemical compositions considered in this article is given in Table I.

Table I
Chemical Composition

Class	Carbon	Manganese	Silicon	Phosphorus	Sulphur
Low carbon.....	below 0.20	0.50-1.0*	0.25-0.75	0.05 max.	0.05** max.
Medium carbon.....	0.20-0.50	" "	" "	" "	" "
High carbon.....	over 0.50	" "	" "	" "	" "

*A.S.T.M. specifications place an upper limit of 0.85% on manganese in castings for railroad use.

**A.S.T.M. specifications allow 0.06% sulphur in acid steel.

Cooling and Cleaning Castings After Pouring—After pouring, castings are usually allowed to cool in the mold to a temperature below the critical range. Cast steel in the unannealed state tends to be tender and brittle. This is especially true of large sections and higher carbon contents and such castings are often shaken out above the critical temperature, partially cleaned and charged to the annealing furnace just below red heat. This procedure is to prevent possible cracking from stresses set up by cooling.

After shaking out and before heat treating, the castings should be cleaned sufficiently to insure thorough and even penetration of heat during heat treatment. If gates and risers are to be nicked and broken off this should be done before heat treating while the steel is less ductile. If the gates and risers are to be removed by flame cutting, this should be done before heat treating in order that the hardened zone adjacent to the kerf may be softened. High carbon steels should be flame cut while still hot.

When thus prepared the castings are subjected to one or more of the heat treatments described below.

Single Normalizing or Single Full Annealing—The castings are placed in a furnace and heated to the temperature given in Fig. 1. Uniformity of heating is important and the rate of heating should be so governed as to insure a reasonable degree of uniformity. This is especially important for heavy sections in order that there will be the minimum lag in temperature between the surface and center.

The purpose of the annealing is twofold: (1) To produce an allotropic change which causes the steel to recrystallize, thus breaking up the very large crystals formed during freezing; (2) To homogenize, or correct by diffusion, the microsegregation of constituents, sometimes known as dendritic segregation, which always occurs during the freezing of an impure liquid such as steel.¹

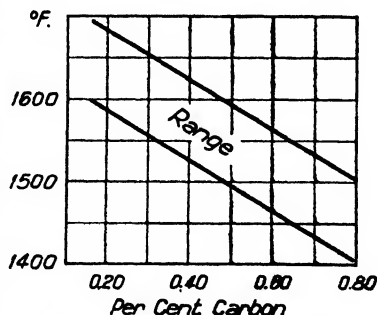


Fig. 1—Temperature range for the heat treatment of steel castings. The lines bounding the "range" indicate the normal lower and upper limits for annealing carbon steel castings with carbon from 0.15-0.80%.

*Prepared by the Subcommittee on the Heat Treatment of Steel Castings. The membership of the subcommittee was as follows: C. E. Sims, chairman; J. H. Hall, H. D. Browne, H. D. Phillips, H. B. Knowlton, and W. C. Hamilton.

¹See page 3 for definition of terms.

²Although complete homogeneity by diffusion is desired and attempted such a state is probably never attained, owing to the slowness with which some elements, such as manganese, silicon, and phosphorus diffuse. It is almost certainly true, nevertheless, that the dendritic structure obtained by macroetching an annealed steel is due to pseudo-morphs of the dendrites that once existed.

The recrystallization is completed as soon as the critical temperature range is passed, but the rate of diffusion is rather slow at this temperature. The rate of diffusion increases rapidly with the temperature, and in order to save time an annealing temperature somewhat above the upper critical range is used. Since both the rate and extent of grain growth also increase rapidly with temperature, too high a temperature is not desired. Therefore, a compromise temperature, which is seldom more than 200°F. above the upper critical range, but which will give diffusion in a reasonable time without excessive grain growth, is used.

Since the size of the primary crystals and, therefore, the degree of microsegregation are increased by the slower freezing of heavy sections the time required for diffusion will vary with the section of the casting. Very light castings which are practically chill cast can be homogenized in less than 1 hr. For heavier sections, experience, backed by some experimental evidence, has dictated a rough guide which is usually stated as 60 min. per in. of heaviest section.

This rule requires some modification. While 1 hr. is usually enough for a 1 in. section the time is not critical. The size of the crystals does not vary as a linear function of section but apparently reaches a maximum in sections somewhere between 6 and 12 in. It is doubtful, therefore, whether any casting however big is benefited by annealing more than 10-12 hr. This time, called the holding time, should begin when the castings are uniformly heated to the annealing temperature. Providing the temperatures are not too high (Fig. 1) overtime heating causes little change in the physical properties.

Normalizing vs. Full Annealing—In general, normalizing produces higher yield and ultimate strength than full annealing. Ductility is approximately the same after either treatment, but normalizing often gives higher impact resistance. There is less separation of ferrite and pearlite in normalizing. Full annealing gives a softer steel and greater freedom from stresses, but ties up furnace equipment for a longer time.

Double Treatment—As was pointed out in regard to single annealing the conditions favorable to rapid and complete diffusion and fine grain are quite dissimilar. Inasmuch as both homogeneity and fine grain are highly desirable for optimum physical properties in a steel, a double heat treatment is often employed. For the first treatment temperatures and times similar to those advocated for single annealing may be used but sometimes higher temperatures or longer times are used. In this treatment homogeneity due to diffusion of the contained elements is approached, but, unless the steel is resistant to grain growth, the grain structure is made relatively coarse.

The second treatment is designed only to refine the grain and the temperature used is just above the upper end of the Ac₁ range. Because grain growth is partly a function of time, the time used in the second treatment should be just long enough to insure uniform heating of the castings to the desired temperature.

Tempering or Stress Relief Annealing—After the normalizing treatment (seldom after full annealing) a treatment below the lower critical temperature may be given at the discretion of the operator. This may be for one or both of the following purposes: (1) To remove stresses set up in the castings by nonuniform cooling; and (2) To improve the ductility and impact resistance of the steel with some sacrifice of strength.

For the removal of stresses, temperatures below about 500°F. are of little value and temperatures above 1000°F. are unnecessary. As a rough guide, it has been found that a temperature of 750°F. will reduce the stresses approximately 50% and 1000°F. will reduce them over 90%.

Except in special cases, the time the castings are held at the tempering temperature should be at least sufficient to insure complete equalization of the temperature throughout the heaviest section of the casting. After reaching the temperature a common holding time for light and medium weight castings is 2 hr. Times of 5-10 hr. are used for heavy castings with sections a foot or more in thickness.

Ordinarily temperatures below 1000°F. have no effect on strength or ductility in a normalized steel. Temperatures above 1000°F. up to 1300°F. progressively lower the strength and increase the ductility in moderate degree. The effect of such temperatures is also progressive with time but at a constantly diminishing rate. Holding times over 2 hr. are probably of little value.

Oil and Water Quenching Steel Castings—When exceptional physical properties, high degree of structural refinement, and resistance to wear are required, heating

and quenching will greatly assist in producing the desired results. When the carbon content of the castings is above 0.30% or when the manganese is high (0.85-0.95%), quenching and tempering are especially effective in producing these requirements. If quenching is for hardening it should be borne in mind that carbon steels are shallow hardening and that, in the medium carbon ranges even with water quenching, only a thin shell or case will be effectively hardened. The higher carbon steels, of course, are deeper hardening. Quenching for the purpose of toughening is not confined to light sections.

For maximum properties and to minimize the danger of cracking, it is recommended that castings should be annealed or normalized before quenching, although for some work this is not essential. The argument for this is similar to that for double normalizing. A coarse grained martensite is less tough and more apt to crack than one that is fine grained.

When water is used as the quenching medium, the temperature of the water should preferably be maintained at 125-150°F. for the higher carbon contents. With carbon under 0.40% the quenching may be more drastic.

When the size and design of the castings are such that quenching might cause cracking if kept in the water or oil until cold, the castings should be removed from the quenching bath when they have become black, but are still hot enough to dry the water quickly; or in the case of oil, the castings should be hot enough to cause the oil to smoke freely on the surface of the casting. This temperature should not be less than about 400°F.

Differential Quenching—Where it is desirable that only certain portions of the casting shall develop the qualities secured by liquid quenching, differential quenching is followed. In this process certain sections are subjected to a liquid quench, either by dipping or spraying, the rest of the casting being protected from the quenching effect. This quenching is often controlled by a stop watch and requires careful attention. The quenched portions are tempered in some cases to give the desired properties.

Tempering—After quenching, the castings should be tempered immediately. When the load is charged while hot into the tempering furnace, the temperature of the furnace should be approximately the same as that of the castings (about 700°F.). The tempering temperature ranges from 800-1250°F., depending upon the physical properties desired. The higher the temperature, in this range, the lower will be the strength and hardness and the higher will be the ductility and toughness.

The quenching and tempering temperatures are given in Table II.

Table II
Quenching and Tempering of Carbon Steel Castings

Carbon Range	Quenching Temp., °F.	Time at Heat	Quenching Medium and Temp., °F.	Tempering Temp., °F.	Tempering Time at Heat
0.15-0.30	1600-1650	¼ hr. for every in. of dia. or thickness	Water at 70	800-1250*	At least 2 hr.
0.30-0.40	1550-1600	¼ hr. for every in. of dia. or thickness	Water at 125	800-1250*	At least 2 hr.
0.40-0.60	1500-1550	¼ hr. for every in. of dia. or thickness	Water at 125 or oil	800-1250*	At least 2 hr.

*These temperatures are based on the assumption that the castings were first annealed.

*See text for tempering.

Notes on the Process—With some castings that have had considerable machine work performed on them, such as heavy duty gears, it is often considered advisable to remove the machining stresses by heating the castings slowly and uniformly to a temperature of 400-600°F., then cooling in air.

Castings should be charged into the furnace in such a manner that lighter castings will be protected from the heat of the furnace by the heavier castings. Should the castings be of similar section, care must be exercised not to heat too long those on the outside of the charge before the inner ones have reached the annealing temperature.

When charging the furnace, the castings should be piled loosely so that the hot gases will have free circulation throughout the charge. To further insure free circulation of the gases, it is advisable to pile the castings a few inches above the floor of the furnace and so permit free circulation of the hot gases. When cooling

from the normalizing temperature, this practice of piling the castings on racks also insures free circulation of the air.

A sufficient number of thermocouples should be used and so arranged in the furnace and, if possible, in the charge of castings, that the desired temperature can be maintained at the top, center, bottom, and sides of the charge.

Steel castings should be grouped for heat treatment, so that the carbon content of the entire charge falls within one of the carbon ranges given in the recommended practice.

As a basis for determining the physical properties of the metal in the casting, it is commercial practice to use test coupons cut from separately cast blocks or attached to the castings. When attached to the casting they should be so placed that they are properly fed and represent, as nearly as possible, the inherent properties of the metal. Test coupons should be heat treated with the castings they represent.

To check the heating operation and to obtain closer control of the temperature, it is sometimes the practice to distribute several test specimens, for fracture inspection, throughout the charge of castings. The cross sectional dimensions of the specimens should represent the largest cross section of the castings, and the carbon content should be approximately the same as the castings being heat treated. After completion of the heat treatment, an examination of the fractures of the specimens for grain refinement indicates the uniformity of heat distribution without destroying a casting for fracture inspection. This practice is obviously impracticable with very heavy sections.

Table III
A.S.T.M. Specifications for Properties of Cast Carbon Steel

Grade	Tensile Strength, psi.	Yield Strength, psi.	Elong. in 2 in., %	Red. of Area, %
A-1	60,000	30,000	22	30
A-2	60,000	30,000	26	38
B	70,000	38,000	24	36
H	80,000	43,000	17	25

Of the above grades all but A-1 require annealing. Grades A and B cover castings for railroad and miscellaneous uses. Grade H does not apply to railroad use.

Composition and Heat Treatment for Alloy Steel Castings

General—This article is designed to cover the heat treatment of alloy steel castings and applies generally to commercial alloy castings for ordinary construction purposes and not for special uses.

Chemical Composition—Only the so-called low alloy steels are considered in this section. In such steels the carbon range is from 0.15-0.60% and the total alloy content is less than 5%. There are about 75 different alloy combinations that have been recommended or used that fall in this classification. Some have but one special alloying element while others may have as many as four. The list is being constantly revised. Typical compositions and physical properties are shown in Table IV.

Cooling and Cleaning of Castings—The lighter section alloy steel castings should be allowed to cool in the molds to a temperature below the critical range, then shaken out and cleaned of adhering sand before heat treatment. Gates and risers are usually removed by flame cutting while the castings are still warm to avoid the formation of small cracks adjacent to the kerf.

Because of the fact that high carbon and alloy steel castings tend to be weak and brittle before heat treatment and as the stresses set up by unequal cooling are sometimes sufficient to fracture them, large castings often are not allowed to cool in the mold below red heat. Instead they are shaken out quite hot, roughly cleaned of sand, gates and risers removed by flame cutting, and the castings charged to the annealing furnace when just below red heat, or at least above 500°F.

If the castings are to be given more than one heat treatment the gates and risers are often removed by flame cutting after the first treatment, but in any case it is preferably done while the castings are hot.

Heat Treatment—Heat treatments may be classified as follows: Full annealing, normalizing, quenching, and tempering.

Broadly speaking, the benefits of alloys in steel are obtained through their effect on the response to heat treatment, such as a slower critical cooling rate, or resistance to softening during tempering. Full annealing, therefore, would fail to take advantage of these benefits and is seldom used except as a first treatment, to be followed by normalizing or quenching. Probably the main advantage of full annealing is to put the steel in a condition where it is easily machined.

Whether an alloy steel should be normalized or quenched is largely determined by (1) the type of steel and (2) the use to which it is to be put. Some alloy steels attain the optimum combination of properties through normalizing. This is especially true of those steels that have great resistance to grain growth, the so-called fine grained steels.

Many alloy steels require quenching and tempering to develop their best properties. Quenching is also used when high hardness is desired. Some castings which have intricate design or large differences of section are not quenched because of danger of cracking or warping. The steel should be selected to fit the casting and if hardness is desired in a casting that cannot be safely quenched, an air hardening composition may be used.

Normalizing—Both single and double normalizing treatments in general follow the procedure given for carbon steels, and have similar objectives. In the first treatment temperatures (for a given carbon content) may be somewhat higher and times of holding may be longer than for carbon steels because the alloy constituents diffuse somewhat more slowly than does carbon.

Temperatures for the first anneal of from 1550-1700°F., depending on the carbon content, are satisfactory for all the steels in this classification with the possible exception of some molybdenum steels which are sometimes annealed as high as 1750°F. The time of 1 hr. per in. of section is a good guide, subject to the modifications listed for carbon steels.

In the second normalizing the objective is grain refinement and the temperatures used should be from 25-50°F. above the end of the A_c range.* The time should not be longer than required to insure uniform heating and complete solution of carbide in the gamma iron. Some of the alloy carbides such as molybdenum carbide are less easily soluble than is iron carbide and require a longer time for solution. In most cases $\frac{1}{4}$ -1 hr. after reaching uniform temperature is sufficient.

Quenching—Quenching of alloy steels is preferably but not necessarily preceded by a normalizing or full annealing treatment to avoid the coarse grain resulting from the long soak otherwise necessary to attain homogeneity.

After such proper annealing, the castings should be heated slowly and uniformly to the quenching temperature, which is similar to that used for a second normalizing treatment, or 25-50°F. above the A_c range. The time of holding should also be the same as for normalizing.

When water is used as the quenching medium, the temperature of the water should preferably be maintained at 125-150°F., especially for the higher carbon steels.

When the size and design of the castings are such that quenching might cause cracking, if kept in the water or oil until cold, the castings should be removed from the quenching bath while still hot enough to dry the water quickly, or in case of oil, the castings should be hot enough to cause the oil to smoke freely on the surface of the castings. They should be charged immediately into a warm tempering furnace.

Differential Quenching—For information on this practice see article on carbon steel castings.

Tempering—Alloy steel castings should be reheated for tempering as soon as possible after quenching. It is a very general practice to temper normalized alloy castings also but the stresses in the normalized steels are naturally of far less magnitude and it cannot be said that the tempering treatment is necessary for all compositions and designs after normalizing.

The purpose of tempering is to relieve the stresses and brittleness caused by quenching or normalizing and to moderate the hardness, that is, to toughen the material. The temperature to be used depends upon the hardness and physical properties desired. Usually the higher the temperature, up to the beginning of the critical range, the softer and more ductile the steel. For maximum hardness and strength a tempering temperature only sufficient to relieve excessive stress is used.

*The margin used will depend somewhat on the uniformity of the furnace. An average temperature that will insure the lowest temperature above the A_c range should be used.

Table IV
Approximate Compositions and Mechanical Properties of Low Alloy Steels

Type	Approximate Compositions, %							Heat Treatment		Properties			
	C	Mn	Si	Cr	Ni	V	Mo	Full Annealed, °F.	Normalized, °F.	Tempered, °F.	Yield Point in 1,000 psi.	Tensile Strength in 1,000 psi.	Elongation in 2 in., %
C-V	0.22-0.40	0.60-0.90	0.30-0.40	.....	.....	0.15-0.25	.....	.....	1650	1200	48-64	79-94	23-31
C-Cr	0.25-0.45	0.60-0.90	0.20-0.60	0.80-1.10	.....	.....	.....	.....	1650-1550	700-1200	77-67	120-110	14-17
C-Ni	0.20 max	0.60-0.90	0.20-0.60	.....	2.00 min	.....	.....	.....	1750-1550	1250	45-55	75-85	25-32
C-Ni	0.15-0.45	0.50-1.00	0.20-0.60	.....	3.25-3.75	.....	.....	.....	1650	1250	54-60	85-90	28-32
C-Ni	0.20-0.30	0.80-1.00	0.25-0.45	.....	2.00-2.25	.....	.....	.....	1700	1200	55-65	90-105	22-28
C-Mo	0.25-0.30	0.80-1.00	0.30-0.65	.....	.....	.....	0.30-0.50	.....	1800-1650	1280	70-75	90-100	20-25
C-Mn	0.30-0.35	1.20-1.60	0.30-0.40	.....	.....	.....	.....	.....	1700	1200	58-65	83-87	21-28
Cr-V	0.25-0.40	0.60-0.90	0.20-0.60	0.80-1.10	.....	.....	.....	.....	1650	1250	50-55	83-86	24-32
Ni-Cr	0.30-0.40	0.75-0.80	0.20-0.60	0.75-0.90	1.30-1.50	0.15-0.20	.....	1700	1650-1550	1200	65	94	27
Cr-Mo	0.25-0.40	0.40-0.85	.....	0.60-1.00	.....	.....	0.25-0.40	1600	1750-1800	1200	70-85	95-120	15-24
Cr-Mo	0.25-0.30	0.40-0.80	.....	4.00-6.50	.....	.....	0.40-0.60	1650	1550	700	80-90	100-113	15-20
Mn-Ni	0.20-0.40	1.00-1.50	0.40-0.50	.....	0.75-2.00	.....	.....	1650	1600	1200	75	120	23
Mn-Mo	0.25-0.35	0.75-1.50	0.30-0.40	.....	1.25-1.50	.....	0.30-0.50	1850	1700	1100-1200	62-65	90-100	20-29
Ni-Mo	0.35-0.35	0.60-0.80	.....	.....	1.25-1.50	.....	0.30-0.35	1850	1700	1350	65-95	90-120	18-30
Cr-Mn-Si	0.15-0.30	1.00-1.30	0.90-1.10	.....	.....	.....	1.75-1.90	1650	1700	1350	59-62	86-95	23-26
Cr-Ni-Mo	0.12-0.30	0.50-1.00	.....	.....	0.40-0.80	.....	0.20	.....	1700-1650	1200	65-80	89-94	24-33
Mn-Ni-V	0.30	0.90	.....	.....	1.50	0.14	0.30-0.35	.....	1800-1500	1000-1200	60-70	75-90	18-25
Ni-Cr-Mo	0.30-0.35	0.60-0.80	0.35-0.45	0.60-1.00	1.50-2.00	0.08-0.12	.....	.....	1850-1500	750-1050	70-80	100-120	17-23
Mn-V	0.25-0.35	1.20-1.80	0.35-0.45	.....	1.10-1.70	0.04-0.05	.....	.....	1650-1550	1050-1200	60-80	90-110	22-32
Ni-Mn	0.25-0.35	1.20-1.80	0.35-0.45	.....	.....	.....	.....	.....	1750-1550	750-1050	60-75	90-110	22-32
Mn-Ti	0.25-0.33	0.85-1.10	0.35-0.50	.....	1.35-1.65	0.08-0.12	.....	.....	1700-1500	750-1200	60-75	90-105	22-32
Ni-V	0.25-0.33	0.85-1.10	0.35-0.50	.....	.....	.....	.....	.....	1650-1550	700-1250	60-85	100-125	20-30
Cr-Mn-Si	0.20-0.50	1.00-1.80	0.30-1.00	0.20-0.70	.....	.....	.....	.....	.....	.....	.....	.....	.....

*The ranges given are not accidental spreads, and the higher strengths and lower ductilities go with the higher end of the composition range and vice versa.

This is usually from 350-450°F. The maximum tempering temperatures depend on the lower critical temperature but should usually not exceed 1250°F.

The softest and most ductile state is usually obtained by heating just below the critical range for a long period of time, that is, spheroidizing.

Except in special cases, the time the castings are held at the tempering temperature should be at least sufficient to insure complete equalization of the temperature throughout the heaviest section of the casting. After reaching the temperature a common holding time for light and medium castings is 2 hr. Times of 5-10 hr. are used for heavy castings with sections a foot or more in thickness. The discussion on tempering carbon steel castings applies as well to alloy steel.

Uses—The alloy steels listed possess desirable combinations of hardness, strength, and toughness not obtainable with carbon cast steel. The castings are used for locomotive frames, gear blanks, dies, stamps, crusher jaws, pinions, car wheels, shovel teeth racks, chain, valves and fittings, and caterpillar treads. The selection of the alloy depends upon the service required.

Due to their higher physical properties it is possible to obtain greater strength for a given cross section than with carbon steel castings. These alloys, therefore, find a particular application where reduction of weight is important, and where high stresses are encountered.

Notes on the Process—General comments on carbon steel castings apply equally to alloy steel castings.

The straightening of castings is best done while they are uniformly heated to a temperature above 500°F. This operation can be done while the castings are cooling from the normalizing treatment, while heated for tempering, or after a special heating for this purpose.

The physical properties obtained by heat treating alloy castings are destroyed by the local application of heat, such as in welding, flame cutting, or hot straightening.* These operations produce dangerous local disturbances of grain structure, hardness, and excessive stresses. Castings should, therefore, be retreated after such practice, although in some cases a strain relieving treatment will suffice.

The rate of cooling in the normalizing practice is merely relative, depending upon the size of the charge and of the castings. The smaller the load or the lighter the sections, the more drastic the cooling, and therefore, the higher the physical strength. The ductility is not affected materially except for the more extreme changes of cooling rate.

It is commercial practice to use test specimens cut from a separately cast block or from test coupons attached to the casting as a basis for determining the physical properties of the castings. Test pieces or test coupons should be heat treated with the castings which they represent.

*This refers to local heating as with a torch for straightening or bending and not to the regular straightening done while the casting is heated uniformly to a temperature of 500-900°F.

Composition and Heat Treatment of Plain Carbon Steel Gears*

General—This article covers the selection of steel and the heat treatments for gears and sprockets made from plain carbon steel bars or forgings. Because of the wide diversity in the size and service application of gears, it is impossible to give detailed practices applicable to all cases.

All the temperatures recommended in this article refer to the temperature of the stock and not to the furnace temperature.

The steels given in Table I are suitable for gears and sprockets requiring only a moderate degree of strength and wear resistance. Their cost is less than that of alloy steels, and the cost of machining these steels is less than that of medium carbon alloy steels. The strength, hardness, and toughness are somewhat lower than that obtainable with the alloy steels.

It is recommended that the temperature of the furnaces for all heating operations, including the forging furnace, should be under proper pyrometric control.

Table I
Chemical Composition of Carbon Steels for Gears

S.A.E. Steel Nos.	C	Mn	P Max.	S Max.
1035	0.30-0.40	0.60-0.90	0.045	0.055
1040	0.35-0.45	0.60-0.90	0.045	0.055
1045	0.40-0.50	0.60-0.90	0.045	0.055
1046*	0.40-0.50	0.40-0.60	0.045	0.055
1050	0.45-0.55	0.60-0.90	0.045	0.055

Note—A silicon content of 0.15-0.30% is optional. The total of the nickel and chromium content must not exceed 0.20%.

*This is not a regular S.A.E. Steel.

Selection of Material—The chemical compositions of the steels commonly used are given in Table I.

The higher the carbon and manganese content of the steel, the greater will be the surface hardness and the penetration of hardness with any given speed of quenching. As a result, under any given quenching conditions, the higher carbon gears will have more tendency to distort and crack in treatment and to show less shock resistance after treatment. The smaller the gear and the faster the quench the lower must be the carbon and the larger the gear and the slower the quench, the higher must be the carbon. The mill practice and grain size of the steel likewise affect the hardness obtained and the hardness penetration with any given speed of cooling.

Steels 1035 and 1040 are commonly hardened by quenching in water, brine, or caustic solution. Steel 1045 may be water or oil quenched. When cracking in quenching is feared because of the design or the speed of quenching, steel 1046 is recommended. This steel is less prone to quenching trouble because the combined carbon and manganese content is less than 1.10%. Steel 1050 is primarily an oil quenching steel.

Forging—For forging, the bars should be heated to a temperature of 2100-2350°F. The forging temperature is governed by the amount of work to be done. The finishing temperature is important and should be 1600-1850°F.

The upsetting method is preferred because it gives proper grain flow, stronger gears, and less distortion in heat treatment. The upsetting may be accomplished in an upsetting machine or by hammering forgings in such a way that the direction of the blow is parallel to the grain flow of the bar before forging. Where high strength and minimum distortion are not essential, other methods of forging are permissible.

Normalizing and Annealing—In general it is recommended that all forgings should be normalized or annealed to refine the coarse structure produced by the

*Prepared by the Subcommittee on the Heat Treatment of Gears. The membership of the subcommittee was as follows: W. E. Jominy, Chairman; Fred Young, Scott Taylor and H. B. Knowlton.

forging temperature. This treatment will minimize the distortion in subsequent heat treating operations and improve the machinability. When cutting gears from bar stock, annealing or normalizing of the bar stock may be advisable in some cases, but is frequently unnecessary.

The recommended temperatures for normalizing and annealing are given in Table II. The cooling rate depends upon the size of the gears, the carbon content, and the hardness desired. In general plain carbon steel forgings are considered machinable in the normalized condition, although full annealing may improve the machinability.

Table II
Heat Treatment for Carbon Steel Gears

S.A.E. Steel Nos.	Normalizing After Forging, °F.	Annealing After Forging, °F.	Quenching, °F.	Temp., °F.
1035, 1040, 1045, 1046, 1050.....	1650-1750	1575-1650	1500-1550	350-850

When parts are large or the service required is not severe, normalizing or annealing may be the final heat treatment. A variation of these processes called "stack annealing" consists of piling the pieces as they come from the forging hammer or press and allowing them to cool.

Hardening—The gears should be heated uniformly to the temperature given in Table II and under conditions which do not scale, carburize, or decarburize.

The exact hardening temperature depends upon the analysis of steel, the thickness of the section, and the quenching medium employed. The higher the carbon and manganese content and the more severe the quench, the lower should be the quenching temperature. For any given steel and quenching medium, the heavier the section the higher should be the quenching temperature. To help eliminate distortion the lowest quenching temperature, consistent with the other conditions, should be used. When the carbon and manganese are at the high limit in steel 1050, temperatures as low as 1475°F. may be used and when the carbon and manganese are at the low limit in steels 1045 and 1046 temperatures as high as 1575°F. may be required.

Quenching—For quenching these steels, four methods are available as follows:

1. **Oil Quenching**—Oil quenching produces the lowest and shallowest hardness and the least distortion of any of the methods. Where sections are thin, or the carbon and manganese content high, or the least distortion possible must be obtained, this quench should be used. It is not generally suitable for heavy sections. It is common practice to have the temperature of the oil bath somewhere between 90 and 130°F.

2. **Water Quenching**—Quenching in water is applicable to most sections. Cold water quenching produces higher hardness but increases the danger of distortion and cracking. To withstand such quenching, the sections must be reasonably uniform. A combined carbon and manganese content above 1.10% increases the hazard. The heavier and more uniform the section and the lower the carbon and manganese contents, the more drastic may be the quench.

Quenching in warm water produces results intermediate between that of cold water and oil quenching. The danger of distortion and cracking, and the degree and penetration of hardness produced, decrease with increase of the temperature of the water. Bath temperatures above 130°F. are not usually recommended.

3. **Time Quenching**—Time quenching in water is used in connection with those parts which, because of either composition or design, cannot be completely quenched in water. The operation is carried out by allowing the piece to remain in the quench only until such time as it contains enough residual heat in the center of the heavier sections to reheat the entire part to a temperature approaching that used for tempering. At this point the piece is withdrawn from the quench and allowed to cool in the air until the residual heat has been distributed as evenly throughout as possible. After this it may be cooled in any convenient manner. The use of automatic devices for timing the quench and ejecting the gear is desirable. If the time quenching is carefully done and the hardness range on the finished gear is not too close, the tempering operation may be omitted, but it is safer to temper the gear the same as if completely quenched.

4. *Caustic Soda Solution*—A very severe quench is obtained by using a water solution containing a minimum of 4% caustic soda by weight. Such a quenching bath will operate satisfactorily up to 130°F. When used warm it is less likely to produce cracks than a water quench but at the same time it produces a high and deep hardness in the treated parts. This quench is of particular advantage when sections are heavy or the steel has a tendency to harden erratically in other quenching baths.

5. *Quenching from Cyanide*—A satisfactory gear can be made from 1010 steel with a 0.002-0.010 in. cyanide case. Where a deeper case is desired an activated cyanide bath may be used. A deeper case may also be obtained by carburizing. Cyanide hardening improves wearing surfaces. For example, if steel 1045 is quenched in oil from a cyanide bath, a file hard and serviceable gear should be obtained.

When small or finer pitched teeth necessitate the lower carbon steels, they should be given the cyanide treatment. The low carbon steels do not produce a good tooth finish. The quenching temperatures indicated in Table II should also be followed when heating in cyanide.

For 1010 to 1030 steels, the minimum cyanide bath temperature should be 1550°F. and in all cases above the A_c critical point.

Tempering—Tempering consists of reheating the gears to some temperature below the critical temperature of the steel in order to relieve strains, reduce hardness, and induce toughness. These results are accomplished simultaneously and are increased in degree with increase of time and temperature. All sections should be brought to the proper temperature and held for 15 min. to several hr., depending upon the size and type of gear.

The tempering temperature used will be governed by the hardness required in the finished gear, by the reaction of the parts to the quench, and by the peculiarities of the mill heat of steel from which the gears are produced. Because the reaction to quenching varies in different mill heats, there will be a variation in the hardness produced. There may also be a variation in the response of some heats to tempering. These conditions necessitate a variation in the tempering temperature in order to produce gears within any specified hardness range.

In Table II a tempering range of 350-850°F. is given. Tempering at temperatures above 850°F. will aid machining operations performed after heat treating, but will reduce the surface hardness below that usually required on heat treated gears.

Hardness—Because of the diversity of application, gears are used over the entire range of hardness that is obtainable in the material. It is, therefore, impossible to recommend hardness limits, but for any specific part a hardness range as narrow as practicable should be specified.

Testing—It is recommended that two teeth 90° apart be selected for hardness testing.

Periodic tests to determine tooth strength, fracture and microstructure are valuable in safeguarding the quality of the product.

Composition and Heat Treatment of Oil Hardening Alloy Gears*

General—This article covers the process to be followed in the heat treatment of oil hardening gears. It is recognized that the size, composition, and type of gears govern entirely the heat treating process. This article, therefore, pertains only to gears of approximately the size of automotive transmission gears.

All the temperatures recommended in this article refer to the temperature of the stock and not to the furnace temperature.

Chemical Composition—The alloy steels most commonly used for gears, together with their chemical compositions, are listed in Table I.

Table I
Approximate Chemical Composition

S.A.E. Steel Nos.	C	Mn	Cr	V (Min.)	Ni	Mo
2345	0.40-0.50	0.60-0.90	.....	....	3.25-3.75	.....
3140	0.35-0.45	0.60-0.90	0.45-0.75	....	1.00-1.50	.....
3150	0.45-0.55	0.60-0.90	0.45-0.75	....	1.00-1.50	.....
3250	0.45-0.55	0.30-0.60	0.90-1.25	....	1.50-2.00	.....
3440	0.35-0.45	0.30-0.60	0.80-0.95	....	2.75-3.25	.....
4145	0.40-0.50	0.60-0.90	0.80-1.10	....	.....	0.15-0.25
4640	0.35-0.45	0.50-0.80	.....	....	1.65-2.00	0.20-0.30
5140	0.35-0.45	0.60-0.90	0.80-1.10	....	.....	.....
5150	0.45-0.55	0.60-0.90	0.80-1.10	....	.....	.....
6140	0.35-0.45	0.60-0.90	0.80-1.10	0.15	.....	.....
6150	0.45-0.55	0.60-0.90	0.80-1.10	0.15	.....	.....

Grain Size and Hardenability—It is a common practice to control the grain size as measured by the McQuaid-Ehn test. Since this test is used to indicate the depth hardness characteristics of steel, it is often desirable to measure this property directly by some form of hardenability test.

Forging Temperature—The steels considered in this article should be forged or upset between 2100 and 2350°F., and it is recommended that the temperature of the forging furnaces should be automatically controlled with pyrometers. It is suggested that finish forging temperature be not lower than 1800°F.

Heat Treatment After Forging and Before Machining—To eliminate forging structure and to obtain desirable machining properties, gear blanks should be normalized and annealed. These heat treatments are given in Table II.

Table II
Normalizing and Annealing After Forging

S.A.E. Steel Nos.	Normalizing		Annealing ¹	
	Temp., °F.	Cool in	Temp., °F.	Cool in
2345	1650-1750	Air	1500-1550	Furnace at 50° per hr. to 900°F.
3140	1650-1750	Air	1500-1550	Furnace at 50° per hr. to 1000°F.
3150				
3250				
3440	1600-1750	Air	1500-1550	Furnace at 35° per hr. to 750°F.
4145	1650-1750	Air	1550-1800	Furnace at 50° per hr. to 1100°F.
4640	1650-1800	Air	1550-1800	Furnace at 50° per hr. to 900°F.
5140	1600-1750	Air	1550-1600	Furnace at 50° per hr. to 1100°F.
5150				
6140				
6150	1650-1750	Air	1550-1800	Furnace at 50° per hr. to 1100°F.

¹When the normalizing is omitted the annealing temperatures should be raised 40°F.

It is common practice to combine these treatments by a so-called cycle treatment consisting of heating to the normalizing temperature, rapid furnace cooling

*Prepared by the Subcommittee on the Heat Treatment of Gears. The membership of the subcommittee was as follows: W. E. Jominy, Chairman; Fred Young, Scott Taylor, and H. E. Knowlton.

to the critical range at approximately 200-250°F. per hour, and holding in the critical range until a proper structure is developed, usually requiring several hours, then furnace cooling to the temperature indicated in Table II.

After these heat treatments, the Brinell hardness number should be between 187 and 207. However, the Brinell hardness is not always indicative of good machining qualities, so microscopic inspection should show lamellar pearlite with a minimum amount of free ferrite or spheroidization.

Heat Treatment of Finished Machined Gears—After machining and cutting the teeth, the gears are hardened and tempered.

Heating for Quenching—The gears are heated slowly and uniformly to the quenching temperatures given in Table III, and held for sufficient time to assure complete and thorough penetration of heat. The heating medium should be so selected that scaling and decarburizing are held to a minimum.

To prevent excessive wear, and to produce a file hard surface, it is recommended that the gears should be heated in a medium (such as cyanide) or in an atmosphere producing a light carburized case; otherwise, the gears should be dipped into a medium such as cyanide after heating.

Quenching—The gears are quenched from the quenching temperature in oil as indicated in Table III. The quenching oil should be maintained constant within a suitable temperature range with a minimum variation consistent with the grade of oil used. It is common practice to keep within the temperature range of 90-130°F.

The best results are obtained by free circulation of oil around the gear being quenched. The formation of gas pockets should be avoided. In some cases special quenching fixtures are advantageous in producing rapid and uniform cooling, which eliminates distortion. The speed of cooling depends somewhat upon the rapidity of circulation of the oil.

Table III
Heating, Quenching, and Tempering of Gears

S.A.E. Steel Nos.	Heating for Quenching—		Tempering Temp., °F.
	Temp., °F. ¹	Quenching Medium	
2345	1380-1420	Oil	400-450
3140	1480-1520	Oil	400-450
3150	1440-1480	Oil	400-450
3250	1420-1460	Oil	400-450
3440	1400-1440	Oil	400-450
4145	1500-1540	Oil	450-500
4640	1440-1500	Oil	400-450
5140	1500-1540	Oil	400-450
5150	1480-1520	Oil	400-450
6140	1500-1540	Oil	400-450
6150	1480-1520	Oil	400-450

¹If the gears are quenched from liquid heating media the temperature may be dropped 20°F.

Tempering—After quenching, the gears are reheated to the temperature given in Table III and held for at least ½ hr. For tempering, either a liquid or a circulating air heating medium is satisfactory.

Notes About the Process—Upset gear blanks produce teeth of uniform strength all the way around, whereas, pegged out flats when drop tested usually reveal strong teeth on two sides of the gear and weak teeth on two sides between the strong teeth.

Inspecting and Testing—At least two teeth 90° apart on every gear should be polished and tested for hardness. After quenching and tempering, the Rockwell hardness should be C-52-C-57. Special fixtures are of advantage for obtaining the hardness tests.

Specimens should be broken periodically under a drop hammer to check up on the forging and heat treating methods.

Cleaning—It is recommended that after quenching the gears should be properly washed to remove all oil before tempering, and that after tempering they should be cleaned by a suitable process.

Heating, Forging, Annealing, and Normalizing Locomotive Forgings*

Introduction—This article is to be used as a guide in the manufacture and heat treatment by annealing or normalizing of locomotive forgings, such as locomotive driving and traller axles, crank pins, main and side rods, piston rods, and similar forgings. The heat treatment of certain classes of such forgings by quenching in a liquid medium followed by tempering, which may also be done, is not covered by this article.

Heating Billets for Forging—As rapid heating may produce internal ruptures, care must be taken to avoid it, particularly from the low temperatures. Ample time should also be given for the heat to penetrate uniformly and thoroughly into the billet before forging. The actual heating time required will depend on the type of steel and the equipment and methods used for heating.

Cold billets should not be charged into a hot furnace. Billets that have been stored outdoors, particularly during winter months, should be brought into the shop for a warming period of 10-12 hr. before being charged into the furnace for heating.

Preheating Forging Billets—It is good practice to preheat the billets. This is best done in a separate furnace or one with a preheating chamber. If such a furnace is not available, the billets can be charged into a forging furnace after the operations for the day are completed, and the furnace has been cooled down to a dull red. The billets will absorb the furnace heat and by the next morning will be preheated to a temperature of several hundred degrees Fahr. They are then ready for direct firing, which should proceed slowly. When a separate furnace is available for preheating, the billets are charged into the cold furnace and brought up slowly and uniformly to a temperature of 1100-1200°F. The time required to heat to this temperature should be approximately three-quarters of an hour to an hour per inch of least thickness.

To avoid loss of heat, the billets should be transferred quickly from the preheating furnace to the forge heating furnace. As the danger of rupturing the billets has been practically eliminated by preheating, the forging furnace can be at considerably higher temperature than the preheated billets. Raising the preheated billets to the forging temperature is carried out with the usual precautions to insure uniform heating and thorough penetration of the heat. The minimum time required to bring preheated billets from a temperature of about 1100°F. to the forging heat (2100-2200°F.) is approximately one-half hour to one hour per inch of least thickness. For billets of various thicknesses, the following heating schedule is typical:

8x 8 in.....	3 hr.	10x10 in.....	4 hr.	12x12 in.....	5 hr.
14x14 in.....	6 hr.	16x16 in.....	7 hr.	18x18 in.....	9 hr.
12x 6 in.....	3 hr.	14x 8 in.....	4 hr.	20x 8 in.....	4 hr.

Forging Temperatures for Billets—The proper forging temperature for both carbon and alloy steel billets, of the types generally used for locomotive forgings, is 1900-2100°F., which is an orange to yellow heat. Overheating and uneven heating must be avoided, as both are sources of forging ruptures. It is desirable to have the heating furnace under pyrometric control, preferably by thermocouples.

The temperature at which the forgings are finished will be determined by the initial forging temperature, and by the temperature lost during forging, which depend respectively on the size of the forging and on the amount of work required to shape the forging from the billet. Generally, they are finished at a temperature of 1500-1700°F. Lighter sections, such as connecting rods, are usually finished at the lower temperature, while heavy sections, such as driving axles, are finished near the higher temperature mentioned.

Heat Treatment of Locomotive Forgings—After the forging operation is completed, the forgings should be allowed to cool to below the critical range under suitable conditions to prevent injury by too rapid cooling. To remove forging stresses and to refine the grain, an appropriate heat treatment should then follow.

*This article was prepared by the Subcommittee on the Heat Treatment of Locomotive Forgings. The membership of the subcommittee was as follows: M. A. Herzog, Chairman; J. H. Higgins, J. A. Succop and P. E. McKinney.

The heat treatment may consist of annealing, but it is the usual practice for high duty locomotive forgings in which better physical properties are required, to receive a treatment consisting of normalizing followed by tempering.

When forgings are to be bored or rough machined, preliminary to normalizing and tempering, they may be annealed to improve their machinability.

Annealing—The purpose of annealing a forging is to refine the grain structure, increase the ductility, or soften it for ease of machining. Annealing consists of heating to a temperature above the critical range, holding a sufficient length of time at that temperature, and then cooling in the furnace or under other suitable conditions to secure uniform retarded cooling.

Normalizing and Tempering Locomotive Forgings—The purpose of normalizing locomotive forgings is to refine the grain structure and to secure the highest combination of physical properties without resorting to quenching in a liquid medium. The temperature must be held a sufficient time to permit complete grain refinement in the forgings.

Normalizing may consist of a single heating to a temperature above the critical range followed by cooling in the air, or of a sequence of such heatings and coolings. If a sequence of heatings and coolings is used, the temperature may vary. A decrease in temperature is usually made for each successive heating, but the temperature for each heating should be above the critical range. Normalizing should be followed by tempering.

To eliminate the lack of uniformity in the grain structure of forgings, resulting from variations in reduction and finishing temperatures, and to produce a homogeneous grain structure throughout the forgings which will respond uniformly to the usual normalizing temperature, it is often desirable, particularly with large forgings, to first normalize the forgings at a temperature much above the upper critical limit (approximately 1750-1850°F.).

Tempering—The purpose of tempering is to remove strains set up in the forgings during the cooling from the normalizing temperature. The ductility of the forgings is increased by tempering, while the tensile strength may be slightly reduced. Tempering is not intended to change the grain size, therefore the temperature is below the critical range. After tempering, the forgings may be cooled in the air, slowly with the furnace, or under other conditions to secure uniform retarded cooling. The forgings should be held at temperature a sufficient time to insure complete penetration of the heat.

In annealing, normalizing, and tempering, the choice of temperatures used, the number of normalizing treatments, the length of time that the forgings are held at temperature, the method of cooling in annealing and tempering, all must be determined by experience, taking into account the type of steel, the size and character of the forgings, and the condition of the furnace used.

Temperatures and Times of Heating—In view of the large number of variable conditions involved, it is impossible to lay down exact rules of procedure for annealing, normalizing, and tempering, with stated temperatures and times of heating which will be applicable under all conditions. The following sections give general information regarding temperatures and times of heating which may be expected to give satisfactory results under favorable conditions. The information is given only as a guide and not as standard practice for all cases. Experience based on the actual conditions involved will sometimes show that better results are obtained by the use of other temperatures.

Table I.
Heating and Holding Time for Forgings

Thickness of Largest Section of Forging	Approx. Time of Heating, Hr.	Approx. Time of Holding, Hr.
		Medium Charge
Up to and including 5 in.....	8	{ Carbon steel, $\frac{1}{2}$ hr. per in. of dia. or max. thickness. Alloy steel, $\frac{3}{4}$ hr. per in. of dia. or max. thickness.
Over 5 in. and including 8 in.....	8	
Over 8 in. and including 10 in.....	10	
Over 10 in. and including 12 in.....	12	

The rate at which forgings are heated to the normalizing and tempering temperatures must not be too rapid or the forgings may be injured. The proper rate will depend to a considerable extent on the design of the furnace. In general, the time allowed for each inch of diameter or thickness of the forging should be 45 minutes for raising to the normalizing temperature and 30 minutes for raising to the tempering temperature.

After the temperatures desired for normalizing have been reached, the forgings should be held at these temperatures a sufficient time to permit the desired changes in structure to be completed. A holding time of $\frac{1}{2}$ hr. for C and $\frac{1}{2}$ hr. for alloy steels per in. of dia. or max. thickness will usually be found satisfactory.

Table I gives, for general guidance, the time for heating and holding a medium furnace charge of forgings.

Normalizing and Tempering Temperatures—Table II gives, for general guidance, temperatures which may be used in normalizing and tempering forgings of the various compositions as indicated. The figures are based on a single normalizing treatment with slow cooling in the furnace from the tempering temperature. As previously stated, the temperatures may require modification to meet individual requirements.

Table II
Normalizing and Tempering Locomotive Forgings

C	Mn	Si	V	Ni	Normalizing Temp., °F.	Tempering Temp., °F.	Approx. Ten. Str., Psi.
0.40-0.45	0.50-0.85	0.18-0.30	.....	.....	1500-1550	1000-1100	80,000
0.45-0.50	0.50-0.85	0.18-0.30	.....	.....	1475-1525	1100-1250	80,000
0.50-0.55	0.50-0.85	0.18-0.30	.....	.....	1450-1500	1200-1350	80,000
0.45-0.50	0.70-0.95	0.18-0.30	0.15-0.25	.....	1575-1650	1050-1250	95,000
0.50-0.55	0.70-0.95	0.18-0.30	0.15-0.25	.....	1575-1650	1050-1250	95,000
0.35-0.40	0.50-0.80	0.18-0.35	.....	3.25-3.75	1425-1450	1000-1150	90,000
0.40-0.45	0.50-0.80	0.18-0.35	.....	3.25-3.75	1400-1425	1050-1200	90,000
0.20-0.30	0.80-1.00	0.18-0.35	.....	2.50-3.00	1425-1475	1000-1200	80,000

Annealing temperatures will usually be lower than the normalizing temperatures. The difference is approximately 50°F. lower for annealing the plain carbon steels, 25°F. lower for the nickel steels, and 100°F. lower for the vanadium steels.

Appendix—The following information was taken from specifications of the Association of American Railroads, covering the chemical and mechanical properties of railroad forging of carbon and alloy steels:

A. A. R. Specification M-102-34—Chemical Composition—The steel for grade 3 shall conform to the following requirements as to chemical composition, given in per cent: C, 0.40-0.55; Mn, 0.50-0.90; P, 0.045, max.; and S, 0.05, max.

Tension Tests—Grade 3 forgings shall conform to the following minimum requirements as to tensile properties:

Unannealed Condition

Size, Outside Dia. or Over-all Thickness	Tensile Strength, Psi.	Yield Point, Psi.	Elongation in 2 in., %		Reduction of Area, %	
			Inverse Ratio	Not Under	Inverse Ratio	Not Under
Not over 8 in.	75,000	0.5 ten. str.	1,600,000 ÷ ten. str.	18	2,200,000 ÷ ten. str.	24
Over 8-12 in., incl..	75,000	0.5 ten. str.	1,500,000 ÷ ten. str.	17	2,000,000 ÷ ten. str.	22

Annealed Condition

Size, Outside Dia. or Over-all Thickness	Tensile Strength, Psi.	Yield Point, Psi.	Elongation in 2 in., %		Reduction of Area, %	
			Inverse Ratio	Not Under	Inverse Ratio	Not Under
Not over 8 in.	80,000	0.5 ten. str.	1,800,000 ÷ ten. str.	20	2,800,000 ÷ ten. str.	32
Over 8-12 in., incl..	80,000	0.5 ten. str.	1,725,000 ÷ ten. str.	19	2,640,000 ÷ ten. str.	30
Over 12-20 in., incl.	80,000	0.5 ten. str.	1,650,000 ÷ ten. str.	18	2,400,000 ÷ ten. str.	28

A. A. R. Specification M-104-34—Chemical Composition—(a) The chemical composition of the forgings shall conform to the following:

Class	A	B	C
Carbon, %	0.40-0.55	0.40-0.55	0.20-0.30
Manganese, %	0.60-0.90	0.65-0.95	0.65-0.95
Phosphorus, % max.	0.045	0.045	0.045
Sulphur, % max.	0.05	0.05	0.05
Silicon, %	0.15 min.	0.15 min.	0.15-0.35
Vanadium, % min.	....	0.15	....
Nickel, %	....	....	2.50-3.00

(b) The steel shall not show residual alloying metal impurities in excess of the following limits:

Chromium, %	0.15	0.15	0.15
Nickel, %	0.25	0.25	....

Tension Tests—(a) The forgings shall conform to the following minimum requirements for tensile properties:

Class A

Size, Outside Dia. or Over- all Thickness	Tensile Strength, Psi.	Yield Point, Psi.	Elongation in 2 in., %		Reduction of Area, %	
			Inverse Ratio	Not Under	Inverse Ratio	Not Under
Not over 8 in. (4 in. max. wall)	88,000	50,000	2,300,000 ÷ ten. str.	25	3,650,000 ÷ ten. str.	40
Over 8-12 in. (6 in. max. wall)	86,000	48,000	2,100,000 ÷ ten. str.	24	3,320,000 ÷ ten. str.	38
Over 12-20 in. (10 in. max. wall)	84,000	46,000	2,000,000 ÷ ten. str.	23	3,100,000 ÷ ten. str.	36

Class B

Under 5 in.	90,000	60,000	.....	24	.....	48
5-9 in.	90,000	60,000	.....	22	.....	44
9-13 in.	90,000	58,000	.....	21	.....	42

Class C

Under 8 in.	80,000	55,000	.....	28	.....	60
8 in. and over.	80,000	55,000	.....	28	.....	55

Composition and Heat Treatment of Spline Shafts*

General—This article covers the processes to be followed for the heat treatment of spline shafts. A spline shaft is so constructed that it interlocks, either rigidly or sliding, with a part or parts, such as gears. Thus a spline shaft may have one or more keyways, or one or more keys, but it is not customary to have both keys and keyways on the same shaft. Spline shafts are used in two general classes of work, represented by automotive parts and machine tool parts. Short shafts are widely used in automotive parts, whereas long spline shafts are more common in machine tools. No arbitrary dimensions are set in distinguishing between long and short shafts, but in general, shafts not over 12 in. in length or $1\frac{1}{2}$ in. in diameter may be called "short" spline shafts. It should be understood that the selection of a steel for a spline shaft is not limited to the steels discussed, for steels other than those listed have been successfully used. However, it is believed that the lists given include most of those that have been found satisfactory.

Design—As spline shafts in operation are subjected to alternating stresses, their endurance limit of resistance to fatigue is of importance. The shaft should be designed to eliminate unnecessary necks and sharp corners where stresses might be concentrated. Fillets and machined grooves in splines should always be gradually rounded up.

Stiffness is one of the necessary properties of some types of spline shafts, particularly long shafts. Shafts should be designed of sufficient section so that harmful deflection will not occur under the applied load. Where the design is incorrect, the shaft may twist or bend, thus causing undesirable effects due to alternating stress, vibration, and the like, which will be felt in the gears or other moving parts as well as in the shaft. Heat treatment may raise the elastic limit of the steel, but it will not change the modulus of elasticity. For this reason, heat treated shafts may not be any stiffer than untreated shafts, when operating below the elastic limit.

Distortion—Distortion is the trouble most commonly encountered in the heat treatment of spline shafts. To avoid distortion care must be exercised in all operations. The steel must be carefully selected and inspected. If much machining is performed on the shafts, the machining stresses should be relieved by normalizing or annealing before subjecting the shafts to the final heat treatments.

The carburizing and heat treating operations should all be carried out with extreme care. It may be necessary with some carburized spline shafts to omit the double treatment and to carburize at a lower temperature to avoid distortion.

There are many spline shafts made of bar stock of either black hot rolled finish, or bright cold drawn finish. In either case this material is more liable to distortion than a properly normalized forging; and therefore when minimum straightening is essential, spline shafts made of bar stock should be normalized in the same way as forgings unless the straightening operation is considered absolutely necessary on the finished shaft. If hot rolled or cold drawn bar stock is used, it is essential that $\frac{1}{4}$ - $\frac{1}{2}$ in. should first be machined from the outer surface to insure a clean surface for hardening.

Keyways in a spline shaft may cause distortion in quenching. Unless designed with ample section, a shaft with a keyway has less stiffness than one carrying keys integral with the shaft. To minimize distortion in quenching, it is advantageous to have more than one integral key. These keys are equally spaced about the shaft to facilitate equal cooling and to balance the section.

Chemical Composition of Spline Shaft Steels—Three types of steel are commonly used for spline shafts. These are the carburizing, water hardening, and oil hardening types and include the following steels:

Carburizing Steels—1020, 2315, 2320, 2512, 2520, 3115, 3120, 3312, 3415, 4615, 4620, 4815, and Manganese A.¹

Water Hardening Steels—1045, 1335, 2320, 4130.

*This article was prepared by the Subcommittee on Spline Shafts. The membership of the subcommittee was as follows: G. M. Enos, Chairman, H. Stanley Binns, A. H. d'Arcambal, L. A. Danse, H. B. Knowlton, and E. O. Mann.

¹C 0.15-0.25; Mn 0.90-1.10; P 0.04-0.06; S 0.04-0.06; Cr 0.15-0.25.

Oil Hardening Steels—1335,^a 1340, 2345, 3140, 3250, 3450, 4140, 6150, and Manganese B.^a

Selection of Steels for Spline Shafts—Spline shafts which are not to be highly stressed can be satisfactorily made from steel 1020 or 1315. To make the shaft sufficiently stiff, it is sometimes designed large enough so that these steels may be used instead of alloy steels.

For small shafts which are to be carburized, steels 3115, 2512, 3312, 2315, 4615 and 4815 are satisfactory. If the diameter is over 1½ in., the carbon content can be increased slightly without encountering brittleness on quenching. For example, for large shafts steels 3415, 3120, 2320, 2520, 4620, or 4815 are satisfactory.

While the water hardening steels can be used, it should be pointed out that water quenching may result in cracking, particularly if the design is such that the shaft will be susceptible to cracking. Steel 1045, although used for spline shafts, is not entirely satisfactory. It does not always respond uniformly to heat treatment, whereas 1335 does.

The steels designated as Manganese A, B, and 1335 are representative of the manganese structural steels. Steels of this general type are used successfully in spline shafts. They machine freely, have good physical properties and harden without difficulty.

In addition to these manganese steels, steels 1340 and 1345 are used to some extent for spline shafts. These steels contain carbon 0.35-0.45, and 0.40-0.50% respectively with 1.60-1.90% manganese. They do not machine so readily as the manganese steels listed, but have excellent physical properties and are of the oil quenching type.

The oil hardening steels listed are in general quite satisfactory.

Normalizing and Annealing of Carburizing Steels—To normalize the carburizing steels, heat thoroughly to a temperature between 1650° and 1825°F. For best results in machining, the temperature should be at least 50° above the carburizing temperature. Holding too long at elevated temperatures has the disadvantage of causing excessive scaling, if the furnace atmosphere is not properly controlled. Cool slowly, to give the desired machining qualities.

Careful annealing of helical spline shafts is essential, so as to minimize the movement of the helical angle or lead in subsequent heat treatment.

Carburizing—Carburize to a depth to suit individual requirements. The methods of carburizing as given in this Handbook may be followed. The conventional carburizing process (packing the material in a carburizing compound in a box) is satisfactory. Long and short shafts should stand vertically in the box, but uniform heating is essential, which in some furnaces may require horizontal heating at a sacrifice of straightness. The carburizing temperatures and the heat treatments for carburized spline shafts are given in Table I.

Quenching Treatments for Carburized Spline Shafts—There are several possible quenching treatments which may be given. They are as follows: (1) A direct quench from the box, and (2) a single, or (3) double quench after cooling in the box. The factors which govern a choice of methods are: (1) Shock resistance desired, (2) grain growth characteristics of the steel, (3) distortion. Thus in some plants for certain steels, experience has shown that suitable impact values and minimum distortion were obtained on direct quenching from the box. It is common practice, however, to use the single quench, namely, cool in the box after carburizing, reheat to the temperature given in Table I for the single heat treatment, followed by quenching. With the single quenching treatment it is advisable to use lower carburizing temperatures, and if the structure is coarse after carburizing, it is advisable to use the higher reheating temperature (single treatment) as given in Table I. It is, of course, desirable to hold distortion to a minimum. By selecting steels which do not coarsen at the carburizing temperature used, distortion is held to a minimum by direct quenching from the box, or by a single reheat after cooling in the box.

A double quench as given in Table I will give case and core refinement and resistance to shock and impact, without exercising great care in the control of grain size. It is open to the objection that more distortion may occur.

^aC 0.35-0.40; Mn 1.60-1.90; P 0.040; S 0.050.

^aC 0.45-0.55; Mn 0.90-1.10; P 0.045; S 0.050; Cr 0.45-0.60.

Table I
Carburizing and Heat Treating of Carburized Spline Shafts

Steels	Carburizing Temp. ¹ , °F.	Cool in	Reheat ² , °F.	Quench in	Reheat, °F.	Quench in	Only for Single Treatment ³ Reheat to, °F.	Single or Double Treatment Quench in	Tempering Temp. ⁴ , °F.
1020	1600-1700	box	1550	oil	1400-1450	....	1400-1450	water	350-425
2315	1600-1700	box	1540	oil	1375-1400	....	1325-1375	oil	350-425
2320	1600-1700	box	1540	oil	1375-1400	....	1325-1375	oil	350-500
2512	1600-1700	box	1525	oil	1375-1400	....	1300-1350	oil	350-500
2520	1600-1700	box	1525	oil	1350	oil	1350-1450	oil	275-400
3115	1600-1700	box	1550	oil	1400-1425	....	1375-1425	oil	350-425
3120	1600-1700	box	1550	oil	1400-1425	....	1375-1425	oil	350-500
3312	1600-1700	box	1525	oil	1375-1400	....	1375-1425	oil	350-500
3415	1600-1700	box	1525	oil	1375-1400	....	1350-1400	oil	350-500
Manganese A	1600-1650	box	1575	oil	1400-1425	....	1400-1425	oil	300-400
4615	1600-1700	box	1525-1575	oil	1375-1425	oil	1420-1470	oil	275-400
4620	1600-1700	box	1525	oil	1425	oil	1420-1470	oil	275-400
4815	1600-1700	box	1600	oil	1375	oil	1375-1425	oil	275-400

¹Carburizing at the lower temperature causes less distortion, while at the higher temperature more rapid penetration is secured. The tendency is to make 1650°F., the minimum carburizing temperature.

²Many find it desirable to quench from 1450-1550°F.

³There is considerable difference of opinion as to the tempering temperatures that should be used for various steels. For some steels a lower tempering temperature, but not less than 275°F., may be desirable.

For hardening it may be suggested that the spline shafts be hung vertically from eyebolts in the furnace, and also quenched vertically from the same eyebolts on both single and double quenched shafts. Spline shafts are always out in relation to the keyway. Shafts can be quenched in a fixture or on a machine on the final heat, so that they will come straight enough to clean up on grinding when an ample amount of grinding stock is allowed. By using this method, the straightening operation may be unnecessary in many cases.

Spline shafts can also be heated in a horizontal position in a continuous furnace provided the supports are properly spaced. The shafts come out fairly straight although they usually require some straightening.

Tempering Carburized Spline Shafts—In tempering, the highest temperature should be used that will give the desired hardness.

Normalizing and Annealing Water Hardening Steels—To normalize or anneal the water hardening steels for spline shafts, heat openly, exposing maximum surface area, to a temperature of 1600-1700°F. for steel 1045 and to 1650-1750°F. for steels 2320 and 4130. For this treatment the steels should be held at temperature only long enough to insure complete penetration of heat. From these temperatures the steels may be cooled in the air or cooled at a rate to produce the desired machining qualities.

Table II
Hardening and Tempering of Water Hardening Spline Shafts

Steels	Quenching Temp., °F.	Quench in	Tempering Temp., °F.
1045	1475-1525	Water	700-1200
1335	1475-1525	Water	700-1200
2320	1600-1650	Water	700-1200
4130	1475-1525	Water	700-1200

Hardening and Tempering Water Hardening Steels—The quenching and tempering temperatures for the water hardening steels are given in Table II. Before quenching in water, it may be advisable to first quench these steels for a few seconds in oil. The shafts should always be removed from the water before they become cold.

Normalizing and Annealing Oil Hardening Steels—After forging, these steels should be normalized or annealed. The following is a form of normalizing suitable for steels 1335, 2345, 3250, 3450, 6150, and Manganese B, and produces good machining qualities.

Heat the steels slowly, while exposing the maximum surface area, to a temperature of 1650-1700°F. Hold at heat only long enough to insure thorough and uniform heating. Cool rapidly by opening furnace doors to 1280°F. Cool slowly from 1280-1000°F. over a period of from 6-10 hr. for good machining.

Steel 3140 may be normalized by heating slowly and uniformly, while exposing maximum surface area, to a temperature of 1575-1625°F. and cooling from this temperature slowly in air.

Steel 4140 may be normalized by heating slowly and uniformly to a temperature of 1650-1700°F. and cooling slowly in air.

Hardening and Tempering Oil Hardening Steels—The quenching and tempering temperatures for the spline shafts made from oil hardening steels are given in Table III.

Table III
Hardening and Tempering Oil Hardening Spline Shafts

Steels	Quenching Temp. ¹ , °F.	Quench in	Tempering Temp. ² , °F.	Approximate Brinell Hardness
1335	1500-1525	Oil or water	900-1000	255-217
1340	1500-1525	Oil	900-1000	321-255
3145	1425-1450	Oil	900-1050	351-300
	1525-1550	Oil	650- 750	430-375
3250	1475-1500	Oil	475- 750	529-430
3450	1475-1500	Oil	750- 850	460-387
4135	1525-1550	Oil	550- 650	400-387
6150	1575-1600	Oil	700- 800	444-351
Manganese B	1475-1525	Oil	900-1000	400-321

¹Most oil hardening spline shafts are quenched from 1450-1550°F. Many of them are hardened in cyanide.

²Tempering temperatures here suggested may be changed to suit conditions. Some find 400-450°F. satisfactory.

Steel 3145 may be hardened in two different ways, as indicated in Table III. The method giving a high tempering temperature consists in hardening the shaft vertically, with the spline or keyway not cut, and leaving ample stock for grinding. The keyway is then milled after the heat treatment. If the steel has been properly normalized and carefully handled, straightening is rarely needed, but it can be done at the tempering heat if necessary. After tempering, the shafts are rough ground to 0.010 in. large, then the spline is milled, and the spline shafts are finish ground.

This same sequence of operations may be followed for any of the steels listed in Table III. The tempering temperature would then necessarily be higher than indicated in the table in order to make machining possible. By using this treatment on steels 3250 and 3450, more ductility may be obtained than is possible with steel 3145.

Spline shafts may be difficult to straighten after quenching. For example, shafts made with ample grinding stock from steel 3450 may be designed to have either two splines equally spaced or three integral keys, which eliminates the unbalanced distortion. If steels 3250 and 3450 have to be straightened, it is done at the tempering temperature or before tempering.

When steel 3145 is tempered at the lower temperature, the same method as outlined for steel 3450 is used. However, it may be possible to jig or machine quench this steel with a single spline, so that it will come within a reasonable grinding allowance.

Steel 6150 distorts in heat treating more than the steels previously discussed. However, it withstands abuse, and has high strength and fatigue resistance values.

As it has been suggested that straightening may be easier if the grain size is controlled, a 5-7 grain size is recommended. The use of a vertical retort furnace with controlled atmosphere minimizes straightening and grinding.

Composition and Heat Treatment of Small Flat Springs*

Cold Formed From Plates Less Than $\frac{1}{4}$ In. Thickness

General—This article covers the process to be followed in the heat treatment of small flat plates designed for springs used for miscellaneous purposes. The practice includes only springs made from plates less than $\frac{1}{4}$ in. in thickness.

Table I
Chemical Composition of Flat Bars Used for Cold Formed Small Springs

Name of Steel	C	Mn	P Max.	S Max.	Cr	V Min.
Cold rolled	0.45-0.70	0.80-1.20	0.04	0.045	.....	....
Oil tempered	0.55-0.70	0.90-1.20	0.04	0.045	.....	....
Annealed	0.55-0.70	0.90-1.20	0.04	0.045	.....	....
Oil tempered	0.60-0.70	0.30-0.60	0.04	0.045	.....	....
Oil tempered	0.80-0.90	0.30-0.60	0.04	0.045	.....	....
Annealed	0.80-0.90	0.30-0.60	0.04	0.045	.....	....
Cold rolled	0.90-1.05	0.30-0.50	0.04	0.045	.....	....
Cold rolled, Cr-V	0.45-0.55	0.60-0.80	0.04	0.040	0.80-1.10	0.15
Annealed, Cr-V	0.45-0.55	0.60-0.80	0.04	0.040	0.80-1.10	0.15
Oil tempered, Cr-V	0.45-0.55	0.60-0.80	0.04	0.040	0.80-1.10	0.15

Imperfections—The flat bars should be free from surface cracks, hair line seams, surface decarburization,¹ slag inclusions, die scratches, localized segregations, slivers, and cuts. These defects cause premature failure as they are a source of starting points for fatigue.

Hardness—The flat bars as received from the manufacturer should have even hardness in order to obtain uniform results in coiling and forming.

Chemical Composition—The chemical compositions of the steels generally used for cold formed small flat springs of less than $\frac{1}{4}$ in. thickness are given in Table I.

Table II
Heat Treatment of Cold Formed Small Flat Springs

Steel as Listed in Table I	Carbon Range	Quenching Temp., °F.	Quenching Media	Tempering Temp., °F.	Approximate Rockwell "C" Hardness
Cold rolled	0.45-0.70	Cold rolled	...	450-600 ¹	35-40
Oil tempered	0.55-0.70	Pretempered	...	450-600 ¹	35-40
Annealed	0.55-0.70	1450-1525	Oil	700-850	35-40
Oil tempered	0.60-0.70	Pretempered	...	450-600 ¹	35-40
Oil tempered	0.80-0.90	Pretempered	...	450-600 ¹	35-40
Annealed	0.80-0.90	1425-1500	Oil	800-850	35-40
Cold rolled	0.90-1.05	Cold rolled	...	325-375 ¹	35-40
Cold rolled, Cr-V	0.45-0.55	Cold rolled	...	450-650 ¹	35-40
Annealed, Cr-V	0.45-0.55	1575-1625	Oil	850-950	35-40
Oil tempered, Cr-V	0.45-0.55	Pretempered	...	450-650 ¹	35-40

¹Oil tempered and cold rolled flat springs are usually given a short tempering to relieve forming strain.

Heating and Quenching—To prevent excessive scaling the springs made from annealed flat bars should be heated uniformly in a suitable furnace or liquid bath to the quenching temperatures given in Table II. The springs are then quenched rapidly in circulating oil which is maintained at a temperature of 100-140°F.

Tempering—The springs should be heated in a suitable tempering medium to the temperature given in Table II. They should be held at this temperature for a sufficient length of time to permit complete penetration of the heat. The method of cooling after tempering is not important.

*This article was prepared by the Subcommittee on the Heat Treatment of Springs. The membership of the subcommittee was as follows: W. H. Phillips, Chairman; Henry Chandler, H. W. Faus, DuRay Smith, and A. K. Strandberg.

¹Surface decarburization should be maintained at a minimum because recent investigation has demonstrated that decarburization as small as three thousandths of an inch will materially reduce the endurance value of spring steels.

Composition and Heat Treatment of Large Flat Springs*

Hot Formed from Plates $\frac{1}{4}$ in. in Thickness or Over

General—This article covers the process to be followed for the heat treatment of hot formed flat springs both plain carbon and alloy steel. The article includes only springs made from plates of $\frac{1}{4}$ in. in thickness or over and of the type generally used for railway equipment, but also used extensively for miscellaneous applications.

Imperfections—The bars should be free from surface cracks, rolling seams, pipes, surface decarburization,¹ inclusions, and carbide segregation. These imperfections have a tendency to cause early failure of a spring as they are a source of starting points for fatigue. Carbide segregation and inclusions also cause quenching cracks.

Hardness—The steel as received from the manufacturers should be soft enough to permit the simple cold working operations (shearing, punching, trimming, and bending) without cracking.

Chemical Composition—The chemical compositions of the steels generally used for hot formed flat springs of $\frac{1}{4}$ in. thickness or over are given in Table I.

Table I
Approximate Chemical Composition of Steels Used for Hot Formed Large Flat Springs

Steels	C	Mn	P Max.	S Max.	Si	Cr	V
Low C ¹	0.70-0.80	0.50-0.80	0.04	0.04	.....	.....	....
C	0.90-1.05	0.25-0.50	0.04	0.05	.....	.....	....
Si-C	0.90-1.05	0.25-0.50	0.04	0.05	0.25-0.50	.....	....
Si-C-V	0.88-0.98	0.45-0.65	0.045	0.045	0.50-0.75	.....	0.15
Cr-V	0.45-0.55	0.70-0.90	0.040	0.040	.....	1.00-1.20	0.15
Si-Mn	0.50-0.60	0.60-0.80	0.045	0.045	1.80-2.20	.....	....

¹Used for flat springs less than $\frac{1}{4}$ in. in thickness.

Heating for Slotting, Nibbing, Spear-Pointing, and Tapering—For these operations the plates should be heated in a suitable furnace to a temperature not in excess of 1800°F.

Heating for Forming—For forming, the plates should be heated uniformly in a furnace to the lowest temperature at which the steel will work satisfactorily, and in no case should this temperature exceed 1750°F. Generally, the normalizing temperatures given in Table II will be found very satisfactory for the forming temperatures. After forming the springs should be cooled in air until they become distinctly black.

Annealing—When annealing is necessary for machining, to relieve machining strains, cold working strains, or strains from local heating, the steel may be heated to 1250-1325°F. The rate of cooling will vary with the requirements.

Table II
Heat Treatments of Hot Formed Large Flat Springs

Steels As Listed in Table I	Normalizing ¹ Temp., °F.	Quenching Temp., °F.	Quenching Media	Tempering Temp., °F.	Approximate Brinell Hardness
Low C	.....	1450-1475	Oil	700- 850	352-415
C	1575-1600	1500-1550	Oil	850-1050	352-415
Si-C	1600-1625	1525-1575	Oil	850-1050	352-415
Si-C-V	1625-1650	1600-1625	Oil	750-1050	363-429
Cr-V	1600-1625	1600-1625	Oil	850-1050	363-429
Si-Mn	1600-1625	1575-1600	Oil	850-1050	363-429

¹These normalizing temperatures are also often used for the forming temperatures.

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²Surface decarburization should be maintained at a min. because recent investigation has demonstrated that decarburization as small as three thousandths of an in. will materially reduce the endurance value of spring steels.

Heating and Quenching—After the springs have been allowed to cool to a distinct black from the forming temperatures, they should be uniformly reheated in a suitable furnace to the quenching temperatures given in Table II. The heating time in minutes may be determined approximately by multiplying the thickness of the plate by 60.

After being held at temperature for a sufficient time to allow for complete penetration of heat, the springs are quenched in an ample volume of circulating oil which is maintained at a temperature of 100-140°F. The springs should be kept in the oil until they are cooled to a temperature of not more than 300°F. or until sufficiently cold to prevent the oil from flashing when they are removed from the oil.

Tempering—For tempering, the plates should be heated in a suitable tempering medium to the tempering temperatures given in Table II. They should be held at this temperature for a sufficient length of time to permit complete penetration of heat. The method of cooling after tempering is not important. After tempering in a salt bath, a hot water dip removes the salt film from the springs.

Composition and Heat Treatment of Small Helical Springs*

Cold Colled from Wire $\frac{1}{2}$ in. Diameter or Less

General—This article covers the process to be followed in the heat treatment of cold formed small helical springs designed and used for miscellaneous purposes. The practice includes only springs made from wire less than $\frac{1}{2}$ in. in diameter.

Imperfections—The wire should be free from surface cracks, hair line seams, surface decarburization,¹ slag inclusions, die scratches, localized segregations, slivers and cuts. These defects cause premature failure as they are a source of starting points for fatigue.

Hardness—The wire as received from the manufacturer should have even hardness in order to obtain uniform results in coiling and forming. All spring wire sizes of $\frac{1}{4}$ in. and less should be sufficiently ductile to wind on their own diameter as an arbor.

Wires Used in the Spring Industries

Cold Worked Wire (Music Wire)—Music wire is a cold worked wire supplied the spring manufacturers to be made into springs without any further heat treatment, except perhaps a short heating to relieve coiling or forming strains. This wire is of high carbon steel, usually made by the acid process, and its high tensile properties are obtained from its high carbon content and from many passes in the cold working dies or rolls. Its toughness is obtained from a process called patenting. This patenting process consists of passing the hot rolled material rapidly through a furnace at a temperature of about 1800°F. (the wire is at a much lower temperature) and then quenching into lead or air at a speed to produce sorbite, which will enable the steel to withstand severe reduction without developing brittleness. The wire is then cleaned and passed through drawing dies, during which time the coarse grains obtained by the heat treatment are elongated into fibres, producing a wire of great toughness, tensile strength, and particularly torsional strength. This wire is nearly always used in small sizes. Commercial sizes range from 0.004-0.135 in. diameter, and are of a bright surface finish.

Hard Drawn Wire—Hard drawn wire is another cold worked wire furnished the spring manufacturers to be made into springs without any further heat treatment, except perhaps a short tempering to relieve coiling or forming strain. This wire, like the music wire, has its tensile properties enhanced through cold working, but differs from the music wire in that it is simply "process annealed" between passes through the drawing dies instead of "patented." The process anneal consists of heating the wire considerably under the critical range to relieve the cold working strain but leaves the structure undisturbed. The steel in the hard drawn wire is of lower quality than music wire since it is usually made from lower grade material.

Hard drawn spring wire is made from stock with an analysis similar to "oil tempered wire," but it is usually drawn to a lower tensile strength and has a considerably lower yield point. With the same tensile strength, the elastic limit of hard drawn wire is less than for oil tempered wire of the same size.

Oil Tempered Wire—This wire is furnished the spring manufacturers in a heat treated condition, no further heat treatment being required after the wire has been made into springs, except perhaps a short heating to relieve coiling or forming strains. This wire, after having been alternately annealed and cold worked to finished size, is usually heat treated by a continuous process which consists of reeling the wire through shallow tanks of molten lead maintained at 1575-1625°F. The wire is then quenched either into a lead bath whose temperature is slightly above the melting point of lead; into oil which is at a temperature of about 140°F.; or into some other liquid. For tempering, the wire may be heated in an open furnace, in a tank of molten lead, in hot oil, or by bringing it in contact with hot sand or with plates or discs of iron or steel.

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¹Surface decarburization should be maintained at a minimum because recent investigation has demonstrated that decarburization as small as three thousandths of an inch will materially reduce the endurance value of spring steels.

With uniform toughness or ductility, the tensile strength of oil tempered wire varies, being high for small and low for large sizes. This type of wire is heat treated to develop certain uniform qualities of toughness, tensile strength, reduction of area and Rockwell hardness. These properties indicate the ability of the wire to make the severe bends, without fracture required in forming springs.

Annealed Wire—This wire is supplied the spring manufacturers in an annealed condition, and used for springs which are to be hardened and tempered after the wire has been made into springs. After being alternately process annealed and cold worked to finished size this wire is annealed by heating to a temperature of about 1350-1400°F., a temperature which is slightly below the upper critical range of the wire, and which thus produces a partial or complete spheroidization of the carbide. The annealing is usually done in a muffle furnace, a tube furnace, or in lead. Since heat treatment is unsuitable on very fine gage wire because of surface damage and oxidation, tiny springs are made of cold drawn wire instead of being annealed.

Other Kinds of Wire—Other wire materials used for springs are monel metal, brass, phosphor bronze, and many other alloys containing nickel, chromium, manganese, vanadium, molybdenum, tungsten, and silicon, which may be drawn into wire with a reasonably high tensile strength and sufficient ductility for forming springs.

The purpose of various types of special alloys for springs is either to increase fatigue life, to increase resistance to corrosion, or to increase resistance to temperature. The difficulties of producing these alloys in the correct wire size and of sufficiently high strength, as well as the additional cost, limit their use for the manufacture of springs.

Certain grades of stainless steel in the finer sizes may be hard drawn to a tensile strength of at least 75% of that found in music wire and may at the same time retain excellent toughness and ductility for spring purposes.

Low Temperature Annealing—Hardening or tempering of spring wire should not be confused with the low temperature heat treatment after coiling, which is actually a low temperature anneal for the purpose of relieving coiling strains. This anneal may actually increase the elastic limit of the spring wire and increase its resistance to permanent deformation. Springs which will set as coiled may be deflected considerably more after a low temperature anneal without taking a permanent set.

Low temperature annealing for steel may range from 300-800°F., depending entirely upon the stock, the structure of the wire, and the results desired. Usually a temperature of 500°F. will give the maximum benefit.

Chemical Composition—The chemical compositions of steel wires generally used for cold coiled small helical springs made from ½ in. diameter wire or less are given in Table I.

Table I

Chemical Composition of Steel Wire Used for Cold Coiled Small Helical Springs

Name of Wire	C	Mn	P Max.	S Max.	Cr	V Min.
Hard drawn	0.45-0.70 ¹	0.80-1.20	0.04	0.045		
Oil tempered	0.55-0.70	0.90-1.20	0.04	0.045		
Annealed	0.55-0.70	0.90-1.20	0.04	0.045		
Oil tempered	0.60-0.70	0.30-0.60	0.04	0.045		
Oil tempered	0.80-0.90	0.30-0.60	0.04	0.045		
Annealed	0.80-0.90	0.30-0.60	0.04	0.045		
Music	0.80-0.95	0.30-0.50 ²	0.04	0.045		
Annealed	0.90-1.05	0.30-0.50	0.04	0.045		
Hard drawn, Cr-V	0.45-0.55	0.50-0.80	0.04	0.040	0.80-1.10	0.15
Annealed, Cr-V	0.45-0.55	0.50-0.80	0.04	0.040	0.80-1.10	0.15
Oil tempered, Cr-V	0.45-0.55	0.50-0.80	0.04	0.040	0.80-1.10	0.15

¹In small sizes the carbon is often lower.

²The manganese is often lower in some music wire.

Heating and Quenching—To prevent excessive scaling the springs made from annealed wire should be heated uniformly in a suitable furnace or liquid bath to the quenching temperatures given in Table II. The springs are then quenched rapidly in circulating oil which is maintained at a temperature of 100-140°F.

Table II
Heat Treatment of Cold Colled Small Helical Springs

Name of Wire As Listed in Table I	Carbon Range	Quenching Temp., °F.	Quenching Media	Tempering Temp., °F.	Approximate Rockwell "C" Hardness
Hard drawn	0.45-0.70 ¹	Cold worked	...	450-600 ²	40-45
Oil tempered	0.55-0.70	Pretempered	...	450-600 ²	40-45
Annealed	0.55-0.70	1450-1625	Oil	700-850	40-45
Oil tempered	0.60-0.70	Pretempered	...	450-600 ²	40-45
Oil tempered	0.80-0.90	Pretempered	...	450-600 ²	40-45
Annealed	0.80-0.90	1425-1500	Oil	800-850	40-45
Music	0.80-0.95	Cold worked	...	325-375 ³	See Footnote 3
Annealed	0.90-1.05	1450-1625	Oil	800-900	40-45
Hard drawn	0.45-0.55	Cold worked	...	450-650 ²	40-45
Annealed, Cr-V	0.45-0.55	1575-1625	Oil	850-950	40-45
Oil tempered, Cr-V	0.45-0.55	Pretempered	...	450-650 ²	40-45

¹Cushion springs may be 0.35-0.45 carbon.

²Oil tempered and hard drawn wire springs are usually given a short tempering to relieve coiling strain.

³Music wire is purchased according to tensile properties, not hardness.

Tempering—The springs should be heated in a suitable tempering medium to the temperature given in Table II. They should be held at this temperature for a sufficient length of time to permit complete penetration of the heat. The method of cooling after tempering is not important. After tempering in a salt bath, a hot water dip removes the salt film from the springs.

Composition and Heat Treatment of Large Helical Springs*

Hot Coiled From ½ In. Diameter Bars or Over

General—This article covers the process to be followed for the heat treatment of hot coiled helical springs of both plain carbon and alloy steel. The practice includes only large springs made from bar stock of ½ in. diameter or over and of the type generally used for railway equipment, but also used extensively for miscellaneous applications.

Imperfections—The bars should be free from surface cracks, rolling seams, pipes, surface decarburization,¹ inclusions and carbide segregation. These imperfections have a tendency to cause early failure of a spring as they are a source of starting points for fatigue. Carbide segregation and inclusions also cause quenching cracks.

Hardness—The steel as received from the manufacturers should be soft enough to permit the simple cold working operations (shearing, trimming, and bending) without cracking.

Chemical Composition—The chemical compositions of the steels generally used for hot coiled helical springs of ½ in. diameter or over are given in Table I.

Table I
Approximate Chemical Composition of Steels Used for Hot Coiled Large Helical Springs

Steels	C	Mn	P Max.	S Max.	Si	Cr	V
C	0.90-1.06	0.25-0.50	0.04	0.05	.....	.....	....
Si-C	0.90-1.06	0.25-0.50	0.04	0.05	0.25-0.50	.....	....
C-Si-V	0.88-0.98	0.45-0.65	0.045	0.045	0.50-0.75	.....	0.15
Cr-V ¹	0.45-0.55	0.70-0.90	0.04	0.04	.....	0.90-1.15	0.15
Si-Mn ¹	0.50-0.60	0.60-0.90	0.045	0.045	1.80-2.20	.....	....

¹These steels are used in special applications, as for example, in highly stressed helical springs.

Heating for Tapering—For tapering the bars should be heated in a suitable furnace to a temperature not in excess of 1800°F.

Heating for Coiling—For coiling the bars should be heated uniformly in a furnace to the lowest temperature at which the steel will work satisfactorily, and in no case should this temperature exceed 1750°F. Generally the normalizing temperatures given in Table II will be found very satisfactory for the coiling temperatures.

After coiling the springs should be cooled in air until they become distinctly black.

Annealing—When annealing is necessary for machining, to relieve machining strains, cold working strains, or strain from local heating, the steels may be heated to 1250-1325°F. The cooling rate will vary with the requirements.

Table II
Heat Treatment of Hot Coiled Large Helical Springs

Steels As Listed in Table I	Normalizing ¹ Temp., °F.	Quenching Temp., °F.	Quenching Media	Tempering Temp., °F.	Approximate Brinell Hardness
C	1575-1600	1500-1550	Oil	750-1050	352-415
Si-C	1575-1600	1525-1575	Oil	750-1050	352-415
C-Si-V	1625-1650	1600-1625	Oil	750-1050	363-429
Cr-V	1600-1625	1600-1625	Oil	850-1050	363-429
Si-Mn	1600-1625	1575-1600	Oil	850-1050	363-429

¹These temperatures are also often used for the coiling temperatures.

*This article was prepared by the Subcommittee on the Heat Treatment of Springs. The membership of the subcommittee was as follows: W. H. Phillips, Chairman; Henry Chandler, H. W. Faus, DuRay Smith, and A. K. Strandberg.

¹Surface decarburization should be maintained at a minimum because recent investigation has demonstrated that decarburization as small as three thousandths of an inch will materially reduce the endurance value of spring steels.

Heating and Quenching—After the springs have cooled to a distinct black from the coiling temperatures they should be uniformly reheated in a suitable furnace to the quenching temperatures given in Table II. The heating time in minutes may be approximately determined by multiplying the diameter of the steel in inches by 60.

After being held at temperature for a sufficient time to allow for complete penetration of heat, the springs are quenched in an ample volume of circulating oil which is maintained at a temperature of 100-140°F. The springs should be kept in the oil until they are sufficiently cold to prevent the oil from flashing when they are removed from the bath (about 300°F.).

Tempering—For tempering the springs should be heated in a suitable tempering medium to the temperatures given in Table II. They should be held at this temperature for a sufficient time to permit complete penetration of heat. The method of cooling after tempering is not important. After tempering in a salt bath, a hot water dip removes the salt film from the springs.

Heat Treatment of Tool Steels*

(General)

Purpose—Much of the general procedure for the heat treatment of one type of tool steel is applicable to others. These general instructions are to avoid repetitions in the articles on tool steels.

General—Often when correct temperatures are used, many hardening failures result from improper manipulation during heat treatment. The heat treatments given in the tool steel articles apply specifically to certain types of steels, the basic compositions of which are given. This does not imply that such steels are the only suitable ones. These articles are primarily for the purpose of recommending heat treatments.

For information on the relation of design to heat treatment, see page 214.

Forging—For information on the forging of tool steels see the tool steel articles in this section.

Normalizing—*Purpose*—Normalizing implies heating steel far enough above the critical range to carry all carbides into solution and when this is done, it is followed by air cooling; excess carbides may thus be broken up and a more uniform distribution obtained. This operation is more important on pieces that have been forged but should not be necessary on steel that has been annealed by the manufacturer unless subsequently forged.

Some steels should not be normalized. In general, steels that air harden are not normalized, such as high speed steel.

Rate of Heating—Heating tools for normalizing should be done in a manner similar to that described under heating for hardening. Correct soaking time is proportional to the size of the piece. Prolonged soaking will coarsen the grain, rendering subsequent refinement difficult.

Rate of Cooling—The material is cooled from the normalizing temperatures in still air.

Annealing—*Purpose*—Tool steel is annealed to soften it for machining, forming, and grain refinement.

Packing—Steel to be annealed should be placed in a tight container to keep out furnace gases. When pieces are small, they should be packed in cast iron chips, lime, mica, or other neutral material to prevent scaling, decarburization, and too rapid changes of temperature. Care must be taken to keep the steel from contact with the container, and to avoid the presence of scale.

Heating—Heat slowly and uniformly to the temperature desired (see specific tool steel articles in this Handbook).

Holding at Heat—Hold at the annealing temperature long enough for complete penetration of heat, and readjustment of grain. The time will increase with the weight of the charge and the alloy content of the steel, generally 1-4 hr. will be sufficient.

Cooling—Cool slowly, preferably in the furnace, or in mica or other good heat insulating material. In general, the slower the cooling, particularly through the critical range, the softer the steel. As the alloy content of the steel increases the slower the steel must be cooled. The maximum cooling rate of 50°F. per hr. down to 1000°F. is suggested.

Strain Relieving Anneal—This process, sometimes called subcritical annealing, is useful in removing residual strains induced by heavy machine work or other cold working. As indicated, it is usually carried out at temperatures below the critical range (1000-1200°F.). In many cases it is safely done in the open fire but for some tools packing is necessary to prevent scaling and decarburization. Air cooling may be safely used. This treatment often aids in minimizing warpage as well as breakage during hardening.

This practice is usually applied after machining and before hardening but it is often useful to rough machine, then strain relieve anneal before finish machining.

Heating for Hardening—*Rate of Heating*—The rate of heating for alloy tool steels should be proportionately slower than for plain carbon steels as the alloying content increases. In general, the slower and more uniform the heating, the less the warping or change in size or shape, provided other factors are unchanged.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stotz, Chairman; A. S. Jameson, A. J. Scheid, Jr., G. V. Luerssen, W. H. Wills, Burns George, J. E. Erb, F. J. McCarthy, F. F. McIntosh, J. H. McCadle, C. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

Attention is called to the fact that heating for hardening is most rapid in molten baths, somewhat slower in open or semimuffle fuel fired furnaces, and the slowest in electric or complete muffle type furnaces.

Cold tools should be charged at comparatively low furnace temperature (below 1000°F.). Sudden changes in temperature should be avoided, except where steels such as high speed are changed from preheating furnaces to high heating furnaces to obtain rapid heating. It is especially important to avoid sudden changes when reheating hardened steel, to prevent breakage.

The steel should be placed in the furnace so as to expose the maximum surface. It is often advisable to place supports under the tool to raise it from the furnace bottom, thus allowing better heat circulation. An intricate tool should be supported in such a manner as to avoid warping.

Large Sizes—A range of temperature is usually given in recommendations for hardening heats. This does not imply that satisfactory results can be obtained on any tool if held anywhere within that range. Generally the larger pieces are heated to the high side of the range while small pieces are heated to the low side.

Uniform Heating of Tools—Cylindrical tools or intricate parts that have a tendency to heat nonuniformly should be occasionally rotated.

Holding at Heat—Care should be taken to hold the tool at temperature long enough to insure uniform heating throughout the section of the piece. Usually, steel of higher alloy contents will require more time, as noted in specific tool steel articles. This gives a better solution of the carbides but excessive time at temperature may cause some grain growth and surface decarburization, particularly at temperatures well above the critical range.

For the time of holding high speed steel at quenching heat, see the tool steel article covering this steel.

Furnace Atmosphere—Proper control of furnace atmosphere is important and varies somewhat with the type of steel and the temperature used. For certain types of steels which show a tendency to produce a soft skin on the surface such as the oil hardening manganese tool steels, a slightly oxidizing atmosphere will overcome this condition. On the other hand, the best results for hardening high speed and high carbon, high chromium steels are obtained in an atmosphere with high CO and minimum CO₂. In either case, direct impingement on the steel of flames or gases of combustion should be avoided.

Effect of Scale—If tool steel is heated above a low red heat while in contact with scale, even though in a neutral or reducing atmosphere, it will be decarburized. Therefore, care should be taken to keep steel, furnace hearth, and containers as free from scale as possible.

Thermocouples—The thermocouple should be so placed that the flames do not strike it and so located as to indicate as nearly as possible the temperature of the tool. It is generally better to insert the thermocouple through the end or side of the furnace rather than through the top. Pyrometers should be frequently checked. For specific instructions see the article in this Handbook on Pyrometry.

Cooling—Quenching Medium—The quenching medium should vary with the kind of steel treated as well as the speed of cooling necessary for various types of tools. Sufficient volume of coolant should be provided to maintain the quenching medium at proper temperature for uniform results. The use of air as a means of agitation and cooling for liquid baths is not recommended.

Brine—Tools quenched in brine will more readily throw their scale, producing a cleaner surface of more uniform hardness. Brine is a more uniform quench than water when used in still or mildly agitated baths. On work of considerable mass or where definite flow directions are desired, sprays or geysers are necessary. Brine should be maintained at a fairly constant temperature. A range of 60-80°F. is suggested.

Water—Water should be held at a fairly constant temperature, usually between 50-70°F. Fresh tap water is often aerated and may produce soft spots, so that water which has been previously boiled, or has been used frequently, is recommended. When water is used as a quench it should be used in the form of a stream or spray designed to suit the tool to be quenched. The purpose is to circulate the water continuously against the surface to be hardened. This helps to sweep off scale and steam bubbles and results in more uniform hardening. Only small tools should be quenched in still water.

Oils—Oils generally give best results when used between the temperatures of 100-150°F. Avoid quenching in cold oil of not the proper fluidity. Some oils crack or otherwise deteriorate faster than others; consequently, should be reconditioned

as found necessary. Oil baths should be frequently checked for the presence of water. When quenching tools from a cyanide or salt bath, a straight mineral oil should be used to avoid decomposition of the oil.

Air—Certain types of tool steels require air cooling. Air cooling may be applied in three ways: (1) Air blast, which is the discharge from a high pressure line; (2) fan air, which is the current of air discharged from a fan; and (3) still air, which is atmospheric air undisturbed by artificial circulation. When using any one of the three methods the tool should be held or supported so as to allow uniform cooling, as nearly as possible. Caution should be observed in using air blast to apply it through a properly designed device and care taken to avoid the presence of water in the blast.

Special Quenching Media—Unusual conditions often require special quenching media, such as a solution of 5-10% sodium hydroxide in water which has a tendency to overcome soft spots and nonuniform hardening in carbon tool steels. A mixture of water and glycerine in any proportion will produce a rate of cooling intermediate between oil and water. For oil hardening steels the glycerine content is comparatively high (60-90% glycerine) whereas for water hardening steels the glycerine content is low (10-40% glycerine). Mercury can be used to obtain local hardening.

Quenching—Tools should be quenched in such a manner that warping is at a minimum. When immersing tools avoid the formation of gas pockets by vigorous agitation or by jets. It is important that the cooling medium come in contact with all parts of the work to be hardened. Usually tools should not be removed from the quenching bath until they are below 200°F. or to the point where water boils on them, neither should they be allowed to go cold in the quench. A good time to remove the tools is when all of the surface is approximately 125-150°F. Then, if any mass is involved, hold at this temperature until the tools become uniform in temperature throughout. This may be accomplished by placing in an oil bath for the required length of time. The tools are then ready for tempering and may be transferred to the tempering furnace. For specific instructions see the articles on tool steels in this Handbook.

Tempering—Strains—Tools, after removal from the quenching bath and before tempering, are always in a highly and nonuniformly strained condition and danger of cracking is most pronounced. Tools should not become cold before tempering.

Uniform Tempering—Satisfactory tempering results are obtained by heating slowly and uniformly in a freely circulating medium. If a liquid is used, the tools should be placed in a metal basket for immersion which prevents contact with the sides or bottom of the tempering pot.

Charging the Tempering Furnace—When charging tools for tempering, the heating medium should be at a low temperature and the tools still warm.

Rate of Heating—Tools should be brought to heat slowly to prevent rapid release of hardening strains and warpage. Better results are obtained by holding at a lower temperature for a longer time. Generally the length of time should not be less than 1 hr. at temperature, but for specific steels reference should be made to the tool steel articles in this Handbook.

Rate of heat transfer will vary in different heating media. It is most rapid in metallic baths, less rapid in salt and oil baths, and still less in circulated and slowest in still air furnaces.

Cooling from Tempering—Cooling from the tempering operation should be in still air because rapid cooling may induce strains in the steel.

Tempering by Color—Temper colors are the result of slight oxidation of the surface of steel when heated at low temperatures, and are dependent upon time, temperature, and composition of the steel. They are only indicative of the temperature of the surface and do not indicate that the steel has been heated uniformly throughout. Tempering by color is not conducive to uniformity. When necessity requires that tools be tempered by color they should be heated slowly as in other operations and the heat raised progressively to the point or color desired after which further tempering is usually stopped by quenching or withdrawing from the heating medium. The quenching should be done in the least drastic manner, preferably in oil.

General Notes—Warping—The amount of warping on hardening is dependent on the shape of the tool, the kind of steel, the conditions of heating, and the severity of the quench. In general, water hardening steels warp more than oil hardening, whereas air hardening steels show least distortion. Long, thin tools warp more than short, heavy ones.

Some causes of undue warpage are improper tool design, the use of the wrong type of steel, nonuniform or too rapid heating, improper support of the steel while heating, heavy machining or cold working strains (see strain relieving annealing under annealing) insufficient removal of surface, nonuniform quenching, and non-uniform or too rapid tempering.

Soft Spots—Common causes of soft spots are decarburization; improper heating, quenching or bath agitation; gas pockets; tong contact; adhering scale; insufficient removal of surface; or defective furnace bottoms.

Straightening—When necessary to straighten the operation is best performed on the descending heat. Straightening is done by peening, or bending in a vise or on a suitable press with an adjustable control and knife edge rests, so that if one load does not satisfactorily straighten the tool another load can immediately be applied. For straightening on the descending heat, the tools should be withdrawn from the bath at a temperature from 500-600°F., which is just below the point where the oil ceases to flash, or in the case of water quenched tools, just where the water steams or dries off the tools immediately.

Composition and Heat Treatment of Carbon Tool Steels*

(See also the General Heat Treatment article for Tool Steels, page 987.)

General—This article covers the process to be followed in the heat treating of carbon tool steel for general purposes. For specific types of tools refer to the articles in this Handbook for the particular tool in question.

Composition and Application—Carbon tool steel hardens with a hard case and tough interior except in small sizes. By varying the carbon content a wide range of physical properties may be obtained. These factors make it suitable for a great many applications. Thus the lower carbon ranges are used for tools where toughness and resistance to shock are of primary importance, and the higher carbon where hardness, resistance to abrasion, or ability to hold a keen edge are the main requirements.

The type analyses are given in Table I and the range for the carbon content and a few of the more common applications for the steels covered in this article are as follows:

Carbon Content 0.60-0.75%—Hot forming or heading dies for short runs; machinery parts; hammers (sledges and pinch bars); concrete breakers; rivet sets.

Carbon Content 0.75-0.90%—Hot and cold set, chisels, dies, shear blades, mining drill steel, smith's tools, set hammers, swages, flatteners.

Carbon Content 0.90-1.10%—Small cold chisels, small shear blades, large pinchers, large taps, granite drill steel, trimming dies, drills, cutters, slotting and milling tools, mill picks, circular cutters, threading dies.

Carbon Content 1.10-1.25%—Small cutters, small taps, drills, slotting and planing tools, wood cutting tools, turning tools, razors.

Forging—Temperatures for forging are given in Table II. For thin sections use the lower temperature range and for thick sections the higher. Continue forging until a dark red color is reached and then cool slowly in lime or mica.

Table I
Approximate Chemical Composition

Steel No.	C	
1.	0.85	The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.
2.	0.95	
3.	1.10 and over	

Table II
Forging, Normalizing, and Annealing Carbon Tool Steels

Steel No.	Forging ^a			Normalizing After Forging			Annealing ^b		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1. ...	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15-60	1360-1400	Slowly and Uniformly	1-4
2. ...	1800-2000	"	"	1550-1650	"	"	1400-1440	"	"
3. ...	1800-2000	"	"	1600-1700	"	"	1400-1440	"	"

^aThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bCooling rate of 50° max. per hr. to 1000°F.

Normalizing—Place the steel in a furnace so as to expose maximum surface area. Heat uniformly to the temperature given in Table II, and hold at this temperature for sufficient time to obtain complete penetration of heat and for complete solution of the cementite.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stotz, Chairman, A. S. Jameson, A. J. Scheid, Jr., G. V. Luerasen, W. H. Wills, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadie, C. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

Carbon tool steels in larger sections should be heated at the rate of $\frac{1}{4}$ -1 hr. per in. of dia. or thickness and should be held at the normalizing temperature approximately $\frac{1}{4}$ to $\frac{1}{2}$ of the heating time. After properly heating, remove the steel from the furnace and cool in air.

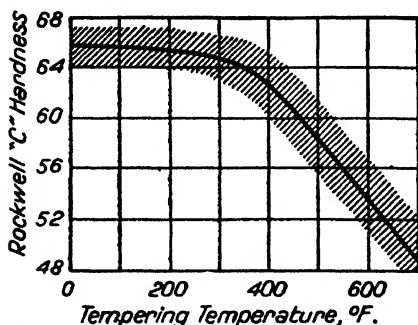


Fig. 1—Hardness of a 0.90% or higher carbon tool steel after tempering.

erably a brine solution of 10% by weight held at a temperature of 70-80°F. Remove the tool from the bath while still warm, but not before it has cooled to about 200°F.

The temperatures in Table III are an average for most tools. Small or intricate sections are quenched from the lower side of the range. A fully hardened carbon steel tool of 0.90% carbon or higher will have a Rockwell C hardness of 64-67 as shown in Fig. 1.

Table III

Heat Treatments for Carbon Tool Steels

Steel No.	Rate of Heating for Hardening	Hardening Temp., °F.	Quenching Medium	Tempering Temp., °F.
1.	Slowly	1450-1500	Brine or Water	300-550
2.	"	"	"	"
3.	"	1400-1475	"	"

Tempering—After quenching, reheat immediately and uniformly to the temperature specified in Table III and Fig. 1. Hold at the temperature for at least 1 hr. then cool in still air.

Suitable Tempering Heats for Various Tools—Temperatures—300-375°F.—Lathe tools for brass and copper alloys, milling cutters for brass and copper alloys, scraper and cutting tools for soft metals, drawing mandrels, drawing dies, bone cutting tools, steel engraving tools, cutting tools for iron and steel, threading dies for brass, gages.

Temperature—375-500°F.—Hand taps and dies, hand reamers, drills, bits, cutting dies, penknives, milling cutters, chasers, inserted sawteeth, press dies for blanking and forming, rock drills, taps and dies, dental and surgical instruments, twist drills, hammer faces, wood carving tools, forming dies, shear blades, reamers, hacksaws.

Temperature—500-650°F.—Bending dies, shear blades, chuck jaws, forging dies, drifts, tools for wood cutting, hammers and drop dies, axes, cold chisels, coppersmith tools, screw drivers, molding and planing tools, hacksaws, butcher knives, saws.

Notes About the Process

Normalizing—A normalizing treatment for all carbon tool steels is recommended after forging and before annealing to obtain a uniform and refined grain structure.

The variation in temperature for the different carbon ranges becomes evident upon a careful examination of the critical range diagram, Fig. 2. A temperature much in excess of that required to produce solid solution (austenite) is conducive to austenitic grain growth and intergranular weakness.

A low normalizing temperature for high carbon steels (1.25-1.50% carbon) fails to break up the massive cementite and results in a brittle structure, since the rate of diffusion of the excess cementite depends upon the temperature. The solubility of carbide in iron is greater as the temperature rises.

Quenching—The quenching temperatures given are average for most tools. Small or intricate sections are quenched from the lower side of the range. Some classes of tools, however, require higher temperatures, such as cold heading and cold striking dies.

The quenching temperature influences the hardness, penetration and final grain size. As these affect markedly the physical properties, uniformity of die life can not be obtained if the quenching temperature is not closely controlled. As absolute uniformity of heating is obtainable only in theory, the best practice is to use temperatures above the A_c critical range as shown in Fig. 1.

Brine or water is the customary quenching medium for carbon tool steels. For details on quenching see the General Heat Treatment Article for Tool Steels.

Microstructure—The microstructure of the annealed steel should consist of carbide particles of a uniform and small size in a background of ferrite. It may or may not contain areas of pearlite not exceeding 25%. It must be free from large carbide particles in the network form. When tools are forged and subsequently normalized and annealed, full consideration should be given to producing the correct microstructure.

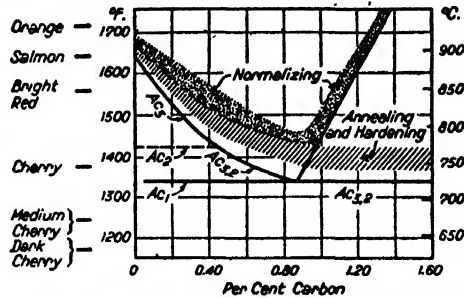


Fig. 2—Critical range diagram for iron-carbon alloys, showing normalizing, annealing, and hardening ranges.

Composition and Heat Treatment of High Carbon, High Chromium Steels*

(See also the General Article on Page 987.)

General—Three general types of high carbon, high chromium steel exist, as indicated in Table I. A large number of steels of individual character may be manufactured and still conform, within reasonable limits, to those listed. When the composition of steels conforms within reasonable limits, the heat treatment will be as recommended, even though properties vary.

Steels of Type 1 class are essentially oil hardening. Types 2 and 3 may be hardened either in still air or by oil quench. These steels are subject to more or less carbide segregation, even to a greater extent than high speed steels, and they are inherently rather brittle particularly in large size sections. Both types are valuable for their remarkable wear resisting properties and low movement in hardening. The air hardening types are tougher and more readily machinable but steels of Type 1 have higher wear resisting properties. The uses of all three classes are somewhat interchangeable. Type 1 should be selected when resistance to wear is of greatest importance and Types 2 or 3 where machinability or toughness is required in conjunction with high wear resistance. The steels are well suited for tools such as blanking, forming and trimming dies, deep drawing dies, wire drawing dies, plug gages, burnishing broaches, thread rolling dies, wood working knives, shear blades, and lathe centers.

Forging—If heated too rapidly or to too high temperature, these steels tend to become hot short. They should be preheated slowly to 1600°F., and soaked thoroughly at the recommended forging temperature. Forging should begin with light blows until the steel has started to flow. Reheat as often as necessary to keep within temperature range recommended in Table II.

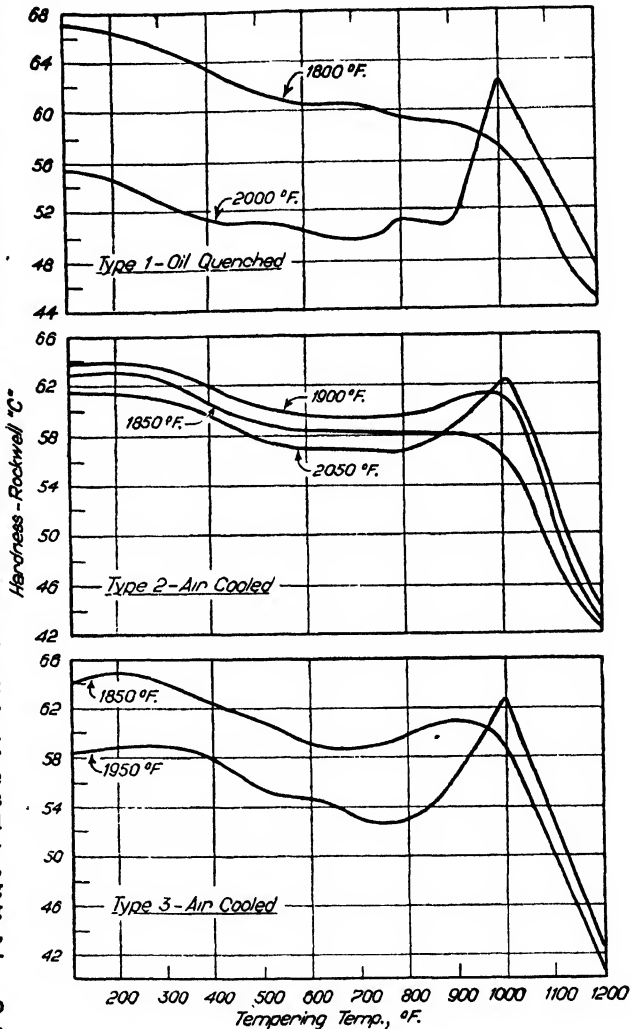


Fig. 1—Hardness and tempering curves for high carbon, high chromium steels.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stolz, Chairman, A. S. Jameson, A. J. Scheld, Jr., G. V. Luerksen, W. H. Wills, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadie, C. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spaulding.

Table I
Approximate Composition of High Carbon High Chromium Steels*

Steel No.	C	Cr	V	Mo	Co
1	2.10	12.00	0-1.00 Opt.		None to 0.50 max.
2	1.50	12.00	0-1.00	0.80	None to 0.50 max.
3	1.40	12.00	Opt.	1.00 max.	3.50

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Table II
Forging and Annealing High Carbon High Chromium Steels

Steel No.	Start °F.	Forging ^b	Rate of Heating	Annealing ^a			
		Do not Forge Below °F.		Temp. °F.	Rate of Heating	Time at Heat	Rate of Cooling
1	1800-1900*	1600	Slowly to 1650	1600-1650	1 hr. per in.	1-4 hr.	Max. 50 per hr. to 1000°F.
2	1800-1900*	"	"	" "	" "	"	"
3	1800-1900*	"	"	" "	" "	"	"

*After forging bury in lime or mica for slow cooling. Do not normalize.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

Annealing—A Brinell hardness of 228 may be considered good for annealed high carbon, high chromium steels. Pack annealing will assist in obtaining lowest hardness results. Since all of the types tend to decarburize on heating, the use of new cast iron chips or charcoal is suggested. Heat uniformly to the temperature recommended in Table II, and hold 1-4 hr., depending on size of charge. Cooling should be done in the furnace at a maximum rate of 50°F. per hr. to 1000°F. Below 1000°F. a faster rate may be used, if desired.

Hardening—All high carbon, high chromium steels tend to decarburize unless heated in specially designed furnaces having properly controlled atmospheres. To prevent decarburization, pack hardening methods are used. Charcoal will carburize at the temperatures recommended in Table III, but may be satisfactory for some types of tools and dies. Where edge strength is desired, spent pitch coke should be used in place of charcoal. Absorption of heat and diffusion of carbides is much slower with these steels than with low alloy tool steels. They should be preheated to 1500°F. and held for complete uniformity, then transferred to the quenching temperature. Soak at the quenching heat will vary with size of dies, but should be about 3 times as long as would be used for similar sized carbon tool steel.

The quenching temperatures recommended in Table III are best adapted for dies and tools because of improved strength resulting from better grain refinement. However, attention is called to the hardness curves obtainable from temperatures in the neighborhood of 2000°F. (Fig. 1). Austenite retained on quenching from this high temperature produces secondary hardening as it transforms in subsequent tempering at about 1000°F. The high quenching temperature may be valuable for

Table III
Heat Treatments for High Carbon High Chromium Steels

Steel No.	Preheat Temp. °F.	Rate of Heating For Hardening	Hardening Temp. °F.	Time at Heat, min.	Quenching Medium	Tempering ^a Temp. °F.
1	1500	Very slowly	1775-1825	15-45	Oil	400-1000
2	"	"	1700-1800	"	Oil	
			1800-1900	"	Air	400-1000
3	"	"	1800-1900	"	Air	400-1000

^aSome people believe it is undesirable to temper these steels between 600-800°F.

use on dies that must resist heat. It is also used if dies or tools are to be nitrided after hardening. High carbon, high chromium steels are readily nitrided either in the ammonia gas process or by tempering at 1000°F. in cyanide bath mixtures.

Tempering—The tempering curves (Fig. 1) indicate hardness obtainable from various temperatures. Tempering below 400°F. is rarely advisable because of the lack of toughness at the lower range. These steels should be heated slowly to the desired temperature to prevent cracking.

Notes—High carbon, high chromium steels often fail in a manner differing from low alloy or carbon tool steels. Where these steels generally require regrinding because of becoming dull, the high carbon, high chromium steels may wear so long that fatigue strains develop and chipping of edges results. In redressing tools or dies after such failure it is advisable to anneal, remachine and reharden, rather than resort to grinding. This treatment will remove fatigue strains and restore new life to the steel.

These steels are difficult to grind in the hardened condition because of their high resistance to abrasion. Unless proper grinding wheels are used heat checks may form. Soft wheels of self dressing character are recommended.

Composition and Heat Treatment of "Nonshrinking" Oil Hardening Tool Steels*

(See also the General Heat Treatment article for Tool Steels, Page 987.)

General—This article covers the heat treatment of the so-called nondeforming, oil hardening tool steels of the types listed in Table I.

Table I
Approximate Chemical Composition*

Steel No.	C	Mn	W	Cr	V
1	0.90	1.10	0.50	0.50	0.20 Opt.
2	0.90	1.60			
3	1.15	0.30	1.60	0.50	0.20

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Application—These oil hardening steels are used for general tools and dies whose design prohibits the use of water hardening steels because of the hazard of distortion or cracking during hardening. They do not usually hold their dimensions as closely as the air hardening type of high carbon, high chromium tool steels.

These steels are relatively deep hardening and are often selected where this is an advantage. In fully hardened small sections, they give around C-65 Rockwell, but as the size of the section increases, the hardness decreases.

Forging—Heat slowly and uniformly to the forging temperature given in Table II. If cold steel is charged in a hot furnace, or if it is heated too rapidly, it may be cracked, especially if unannealed. The steel must be uniformly heated through before being forged, and reheated as often as necessary during forging to keep it within the temperature range given.

The steel should become black before charging in a normalizing furnace.

Normalizing—Always normalize after forging at the temperatures given in Table II. Steel annealed at the mill does not require normalizing unless subsequently forged.

Table II
Forging, Normalizing, and Annealing of Nonshrinking Oil Hardening Steel

Steel No.	Forging ^a			Normalizing After Forging			Annealing ^b		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1800-1950	1600	Slowly to 1500	1650	Slowly to 1500	15-60	1425-1450	Slowly and Uniformly	1-4
2	1800-1900	1600	Slowly to 1500	1550	Slowly to 1500	15-60	1400-1425	Slowly and Uniformly	1-4
3	1800-1950	1600	Slowly to 1500	1700	Slowly to 1500	15-60	1450-1475	Slowly and Uniformly	1-4

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bCooling rate 50° max. per hr. to 1000°F.

Annealing—Heat slowly and uniformly to the temperatures given in Table II. Hold at temperature for sufficient time to obtain complete penetration of heat and refinement of grain. Machining strains may be relieved by a subcritical anneal at 1200°F.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stotz, Chairman, A. S. Jameson, A. J. Scheid, Jr., G. V. Luerssen, W. H. Wills, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadie, C. L. Harvey, M. T. Cousins, J. A. Succop, A. D. Becken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

Hardening—In order to hold distortion to a minimum and to get maximum and uniform hardness, it is advisable to preheat slowly and uniformly at about 1200°F. Then bring up to the hardening temperatures given in Table III. Type No. 2 should be quenched as soon as uniformly heated through—not soaked thereafter. Types 1 and 3 should be soaked a short time at the hardening temperature, in proportion to the size of the piece, before quenching, in order to obtain maximum hardness. Do not soak for minimum distortion.

Table III

Heat Treatments for Nonshrinking Oil Hardening Tool Steels

Steel No.	Preheat Temp. °F.	Rate of Heating For Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1	1200	Slowly	1450-1500	½ hr. for max. hardness*	Oil	325-500
2	1200	Slowly	1400-1475	Do not soak	Oil	325-500
3	1200	Slowly	1575-1625	½ hr. for max. hardness*	Oil	350-550

*No soak for minimum distortion.

If the tool is of intricate design or has abrupt and extreme change of section, it is of great importance to heat slowly in order to prevent breakage and reduce warpage.

Quench in a good quenching oil, the temperature of which should be 100-125°F., but do not cool the steel below the temperature of boiling water.

Tempering—Reheat immediately to the tempering temperature given in Table III.

Notes About the Process—These steels are essentially oil hardening, and over heating of the oil during prolonged and continuous quenching should be avoided. The ratio of bath volume to mass of steel is an important factor. There must be plenty of oil in the bath.

When using a furnace where atmosphere control is possible a slightly oxidizing atmosphere is recommended as a help in preventing "skin softness." If hardening is done in a furnace employing an atmosphere of cracked oil, care must be exercised not to drop the oil too fast or carburization of the surface will result.

The edges and corners of any piece of steel always harden more readily than large flat areas because the cooling medium extracts the heat faster. This is particularly noticeable with fairly large sections of oil hardening steel. In order to crack off the scale and harden the broad, flat surfaces properly, it is advisable to force plenty of oil, usually by means of a pump under good pressure, against these surfaces, and to use the top side of the hardening range.

Composition and Heat Treatment of Tungsten Finishing Steels*

(See also the General Heat Treatment Practice for Tool Steels, page 937.)

General—This article covers the heat treatment of a steel commonly known as tungsten finishing steel, or fast finishing steel.

Composition—There are various minor modifications of composition of tungsten finishing steels. However, the following is typical of the class: C 1.30%; W 3.75%; and Cr 0.25 (optional).

Application—Steels conforming to the above analysis are particularly adapted to finishing cuts where unusually smooth finish is required and for cold drawing dies. The tungsten gives exceptional hardness after water quenching. The extremely hard tungsten carbide particles uniformly distributed throughout the matrix produces great resistance to wear. The combination of hardness and resistance to wear makes this steel suitable for the following applications: Burnishing tools; chilled roll turning tools; cold extrusion dies; corrugating tools; tools for cutting brass, chilled cast iron, hard bone, ivory, marble; dental burrs; drawing dies; fine finishing lathe tools, and rifling tools.

This steel does not possess the red hardness properties characteristic of high speed steels.

Forging—Heat very slowly and uniformly to 1550° and then raise temperature to 1850-1950°F. before starting to forge and finish not below 1600°F. After the forging has been completed, the cooling should be retarded by the use of some insulating material. Do not normalize.

Annealing—Heat thoroughly to 1450-1500°F. and hold at this temperature for a sufficient length of time to insure complete penetration of heat, follow by slow cooling in furnace.

Hardening—Preheat thoroughly at 1200-1300°F., raise the steel to a temperature of 1450-1550°F. Hold at temperature for sufficient time to insure thorough penetration; quench in either brine or water at approximately 70°F. If the lower side of the hardening range is used, it is necessary to hold the steel at temperature for 15-30 min. longer to obtain full and uniform hardness.

Tempering—Following the hardening operation the steel should be removed from the quenching medium while it is still warm and tempered immediately. The tempering temperature varies according to the hardness desired. With a steel similar to the above composition the hardness after quenching from 1600°F., and after tempering should be about as follows:

Rockwell C hardness	
As Quenched	66-68
Tempered, 300°F.	64-66
" 350°F.	64-66
" 400°F.	63-65
" 500°F.	61-63
" 600°F.	59-61

The size and hardening conditions may cause a slight variation from these figures.

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Composition and Heat Treatment of Tungsten High Speed Steel Cutting Tools*

(See also the General Heat Treatment Article for Tool Steels, page 987.)

General—This article covers the heat treatment of 18-4-1, 18-4-2, and the 14% tungsten high speed steels.

Composition—The approximate chemical compositions for the three types of high speed steel considered are given in Table I.

Table I
Approximate Composition of 18-4-1, 18-4-2, and 14% Tungsten High Speed Steel^a

Steel No.	C	W	Cr	V	Mo
1	0.70	18	4.00	1.00	
2	0.80	18	4.00	2.00	0.70
3	0.75	14	4.00	2.00	0.50 Opt.

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Application—These three high speed steels are used for all classes of cutting tools on all types of materials to be cut.

Forging—For forging, heat slowly and uniformly to a temperature given in Table II. It is not safe to continue forging below 1700°F. Slow cooling after forging is necessary to prevent possible cracking from forging strains.

Table II
Forging and Annealing Tungsten High Speed Steel Cutting Tools

Steel No.	Forging ^c			Annealing ^d			
	Start °F.	Do Not Forge Below °F.	Rate of Heating	Temp. °F.	Rate of Heating	Time at Heat, hr.	Rate of Cooling
1 ^a	2050-2150	1700	Slowly to 1600	1600-1650	1 hr. per in. max. thickness	1-4	50° per hr. max. to 1000°F.
2 ^a	2050-2200	1700	Slowly to 1600	1600-1650	Slowly and Uniformly	1-4	50° per hr. max. to 1000°F.
3 ^a	2000-2100	1700	Slowly to 1600	1600-1650	1 hr. per in. Slowly and Uniformly	1-4	50° per hr. max. to 1000°F.

^aAfter forging cool slowly in lime or mica.

^cThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^dDo not normalize these steels.

Annealing—All high speed steel should be annealed after forging and before hardening or when rehardening is required. Box annealing is always preferable. When annealing partially finished tools and generally when surface protection is of prime importance, it is recommended that cast iron chips be used for packing materials.

Heat slowly and uniformly to 1600-1650°F. and hold for complete adjustment and uniformity of grain. Cool in furnace at a maximum rate of 50°F. per hr., until the steel is below 1000°F. The steel should not be taken from the furnace until it is below 1000°F.

After machining and before hardening, it may be necessary to relieve harmful machining strains by annealing at 1200-1350°F.

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Preheating, Heating for Hardening, and Quenching—Preheating—Preheat slowly and uniformly to 1450-1600°F. When hardening large tools or when distortion must be held to a minimum, it is essential to preheat very slowly and uniformly. To accomplish this, it is often advisable to use two preheating furnaces, one held at 1100-1200°F. the other at 1450-1600°F.

Heating for Quenching—Transfer preheated tool quickly to a high heat furnace that is maintained at the temperature given in Table III.

Table III .

Heat Treatments for Tungsten High Speed Steel Cutting Tools

Steel No.	Preheat Temp., °F.	Hardening Temp., °F.	Quenching Medium	Tempering Temp., °F.
1	1450-1600	2250-2350	Oil, Air or Molten Bath	1000-1150
2	1450-1600	2300-2350	Oil, Air or Molten Bath	1000-1150
3	1450-1600	2200-2300	Oil, Air or Molten Bath	1000-1150

In order to obtain the most satisfactory condition, the tool should be brought rapidly to heat in the high temperature furnace. High speed steel tools should be held at high heat sufficient time for proper solution of the carbides without an excessive grain growth or damage to the surface. This should be measured in minutes and seconds.

Quenching—Quench the tool in oil, air, or molten bath. To reduce the possibility of breakage and undue distortion in intricately shaped tools, it is advisable to quench in a molten bath at approximately 1100°F. The tool may be quenched in oil and removed from the bath while still red or at approximately 1100°F. The tool is then cooled slowly in air to 200-300°F., then temper immediately to avoid cracking.

Tempering—Reheat slowly and uniformly to 1025-1150°F. Hold at temperature from 1-4 hr.; the time and temperature depend on the hardness and toughness required.

Straightening—When straightening is necessary, it should be done, if possible, immediately after hardening and before the steel has cooled much below 900°F. If straightening has to be done after tempering the steel should not be allowed to cool much below the tempering temperature.

Notes About the Process—Atmosphere Controlled Furnaces—Atmosphere controlled furnaces satisfy a demand for more accurate dimensional control and a surface not injured during heating for hardening. These furnaces are now available in both electric and fuel fired types where the atmosphere is independent of the source of heat. This permits control of the atmosphere in contact with the work. Small and delicate pieces can be given the heat treatment that will develop the best physical properties of the steel without materially injuring the surface or overheating thin projections.

The ideal atmosphere would be one that is neutral to the steel. The atmospheres now used are the products of combustion of partly burned fuel. They may be cleaned of undesirable constituents and closely regulated as to composition. The best conditions are generally obtained when the hardened steel shows a slightly oxidized surface. Suitable atmospheres will vary with different fuels and equipment. A gas analysis apparatus will help in determining the correct atmosphere.

Salt Bath—With tools that cannot be ground after hardening, or where it is necessary to keep the surface in the best possible condition and preserve sharp edges, salt bath heating will give the best results. The only appreciable change in dimensions will be that of expansion or contraction caused in quenching the tool or by the change in structure of the steel in hardening.

Certain precautions are necessary when using salt baths. Fresh salt has a dissolving action on the steel which disappears after the bath is used a short time. As the bath gets older, a sludge is formed at the bottom of the pot and a heavy crust at the top; these must be removed periodically. As the bath becomes excessively contaminated, pitting, soft surface, or loss of size will occur. An experienced operator can produce satisfactory work by the proper addition of new salt and by avoiding excessive contamination.

Composition and Heat Treatment of Molybdenum High Speed Steel*

(See also the General Heat Treatment Practice for Tool Steels, page 987.)

General—This article covers the heat treatment of high speed steels in which molybdenum is the principal alloying element. The molybdenum high speed steels are relatively new as regards their industrial use, and their chemical compositions are not as definitely established as the 18-4-1 type. These steels decarburize more readily than tungsten types, but with reasonable precautions in heating for forging and hardening this disadvantage can be overcome.

Composition—The approximate chemical compositions of the molybdenum high speed steels considered in this practice are given in Table I.

Table I
Approximate Composition^a of Molybdenum High Speed Steels

Steel No.	C	W	Cr	V	Mo	Co
1	0.80	1.50	4.00	1.00	9.00	
2	0.80		4.00	2.00	9.00	
3	0.80	1.50	4.00	1.50	9.00	5.00

^aThe analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Application—Types 1 and 2 are adapted for most cutting tool applications where a general purpose high speed steel is required. Hardness and toughness compare favorably with tungsten high speed steels. Type 3 is inherently more brittle than 1 and 2, and applications are more limited than the other types.

Forging—These steels can be forged like the tungsten types but at slightly lower temperatures, and some precautions should be taken to prevent excessive decarburization during the heating cycle. (See notes about the Process, below).

For forging, heat slowly and uniformly to a temperature given in Table II. Avoid prolonged soaking at the forging heat and too little reduction. After forging it is desirable to cool slowly down to about 300°F. to avoid possible cracking from forging strains.

Table II
Forging, and Annealing Molybdenum High Speed Steel

Steel No.	Forging ^a			Annealing ^c			
	Start °F.	Do Not Forge Below °F.	Rate of Heating	Temp. °F.	Rate of Heating	Time at Heat, hr.	Rate of Cooling
1 ^a	1900-2000	1650	Slowly to 1500	1550-1600	Slowly and Uniformly 1 hr. per 1 in.	1-4	Max. 50 per hr. 1000°F.
2 ^a	1900-2000	1650	Slowly to 1500	1550-1600	Slowly and Uniformly 1 hr. per 1 in.	1-4	Max. 50 per hr. 1000°F.
3 ^a	1900-2000	1650	Slowly to 1500	1550-1600	Slowly and Uniformly 1 hr. per 1 in.	1-4	Max. 50 per hr. 1000°F.

^aAfter forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^cDo not normalize these steels.

Annealing—Like tungsten high speed steels, these steels should be annealed after forging and before hardening, or when rehardening is required.

Box annealing is always preferable. When annealing partially finished tools,

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and generally when surface protection is of prime importance, it is recommended that cast iron chip be used for packing material.

Heat slowly and uniformly to the temperature given in Table II and hold for complete adjustment and uniformity of grain. The steel should not be taken from the furnace until it is below 1000°F.

After machining and before hardening it may be necessary to relieve harmful machining strains by annealing at 1200-1350°F.

Hardening—The general method of hardening molybdenum high speed steels resembles that followed with 18-4-1, but the hardening temperature (Table III) is lower and more precautions must be taken to avoid decarburization, especially on tools where the surface is not ground after hardening. Salt baths represent an excellent type of equipment for hardening molybdenum high speed steel. (See below.) The use of coke fires or the blacksmith forge is not recommended for hardening molybdenum high speed steels. Tools that have been forged should be machined or rough ground after annealing to remove possible surface defects and reduce the grinding necessary after hardening.

Table III
Heat Treatments for Molybdenum High Speed Steels

Steel No.	Preheat Temp. °F.	Hardening Temp. °F.	Quenching Medium	Tempering Temp. °F.
1	1400-1500	2150-2250	Oil, Air and Molten Bath	950-1100
2	1400-1500	2150-2250	Oil, Air and Molten Bath	950-1100
3	1400-1500	2200-2250	Oil, Air and Molten Bath	950-1100

Preheating—Preheat slowly and uniformly to 1400-1500°F., using the upper part of the range for larger sections. When hardening large tools or when distortion must be held to a minimum, slow preheating may be insured by the use of two preheating furnaces, one held at 1100-1200°F. and the other at 1400-1500°F.

Heating for Quenching—Transfer preheated tool quickly to a high heat furnace that is maintained at 2150-2250°F. The exact temperature depends on the type of tools, the hardening range of the steel, and the furnace atmosphere. In order to obtain the most satisfactory condition, the tools should be brought rapidly to heat in the high temperature furnace and should be held for a sufficient time for proper solution of the carbides without excessive grain growth. Factors affecting this time are temperature, type of furnace, size and shape, and furnace atmosphere. Rate of heat transfer is most rapid in salt baths, and slowest in controlled atmosphere furnaces (see below).

Quenching—Quench the tool in oil, air, or molten bath. To reduce the possibility of breakage and undue distortion in intricately shaped tools, it is advisable to quench in a molten bath at approximately 1100°F. The tool may be quenched in oil and removed from the bath while still red or at approximately 1100°F. The tool is then cooled slowly in air to 200-300°F., then tempered immediately to avoid cracking.

Straightening—When straightening is necessary, it should be done before tempering and, if possible, before cooling to room temperature.

Tempering—Reheat slowly and uniformly to 950-1100°F. Hold at temperature from 1-4 hr.; the time and temperature depend on the hardness and toughness required.

Notes About the Process

Protection of Surfaces During Heating—Due to the tendency of molybdenum high speed steels to decarburize when heated to the forging or hardening temperature range, the use of a borax film or proper furnace atmosphere is helpful in minimizing the decarburization. Borax may be applied by lightly sprinkling over the steel when heated to a low temperature (1000-1400°F.). When a reheat is necessary during forging, more borax should be applied. Small tools heated as above may be rolled in a box of borax.

Another method more suitable for finished tools is to apply the borax in the form of a saturated water solution. In such cases the unheated tools are immersed in the solution at 180-212°F., or it may be applied with a brush or spray. Pieces so treated are heated as usual with care taken in the handling not to scrape off the borax.

When borax is used in a furnace with a Carborundum bottom it is necessary to use a metal pan, preferably of stainless iron, to prevent the borax from fusing with the Carborundum. Such fusion produces a glass like insoluble coating on the tool which is impossible to remove without damage to the cutting edge.

Atmosphere Controlled Furnaces—Atmosphere controlled furnaces satisfy a demand for more accurate dimensional control and surface protection. These furnaces are now available in both electric and fuel fired types where the atmosphere is independent of the source of heat. This permits control of the atmosphere in contact with the work. Small and delicate pieces can be given the heat treatment that will develop the best physical properties of the steel without materially injuring the surface or overheating thin projections.

The ideal atmosphere would be one that is neutral to the steel. The atmospheres now used are the products of combustion of partly burned fuel. They may be cleaned of undesirable constituents and closely regulated as to composition.

The best conditions are generally obtained when the hardened steel shows a slightly oxidized surface. Suitable atmospheres will vary with different fuels and equipment. A gas analysis apparatus will give help in determining the correct atmosphere.

Another method of producing an atmosphere that protects the surface is to heat the tools in a block or muffle of a suitable carbonaceous material. At the hardening temperature an atmosphere high in carbon monoxide is generated. To maintain uniformity, however, the size of the muffle is limited and this method is adapted only to small tools.

Salt Bath—With tools that cannot be ground after hardening, or where it is necessary to keep the surface in the best possible condition and preserve sharp edges, salt bath heating will give the best results. The only appreciable change in dimensions will be that of expansion or contraction caused in quenching the tool or by the change in structure of the steel in hardening. The equipment usually consists of at least three baths—the preheat, high heat, and quenching bath—the function of the latter being to dissolve the high temperature salt from the work so as to facilitate cleaning.

Certain precautions are necessary when using salt baths. Fresh salt has a dissolving action on the steel which disappears after the bath is used a short time. As the bath gets older, a sludge is formed at the bottom of the pot and a heavy crust at the top; these must be removed periodically. As the bath becomes excessively contaminated, pitting, soft surface, or loss of size will occur. An experienced operator can produce satisfactory work by the proper addition of new salt and by avoiding excessive contamination.

Composition and Heat Treatment of Cobalt High Speed Steels*

(See Also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the process to be followed in the heat treatment of cobalt high speed steels.

The composition of the steels as given in Table I covers practically the entire range of cobalt high speed steels now in general use. Cobalt high speed steels not included in Table I may require different heat treatment.

Table I
Approximate Composition of Cobalt High Speed Steels*

Steel No.	C	W	Cr	V	Mo	Co
1	0.75	14	4.00	2.00	0.50	5.00
2	0.70	18	4.00	1.00	0.50	5.00
3	0.80	20	4.00	2.00	0.50	8.00
4	0.80	20	4.00	1.25	0.50	12.00

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Application—Cobalt high speed steels are particularly adapted for cutting hard, gritty or scaly material, such as cast iron, heat treated steels, or sand castings. They do not show the same increased efficiency in the cutting of soft materials as when cutting comparatively hard materials.

Forging—Heat slowly and uniformly to the temperature given in Table II. Do not forge these steels after they have cooled below 1650°F. as cracking may result. After forging, the steel should not be allowed to cool in air but should be buried immediately in some heat insulating material so as to cool slowly, otherwise forging strains may cause cracks in cooling. These steels must be annealed after forging.

Table II
Forging and Annealing Cobalt High Speed Steels

Steel No.	Forging ^a			Annealing ^b			
	Start °F.	Do not Forge Below °F.	Rate of Heating	Temp. °F.	Rate of Heating	Time at Heat	Rate of Cooling
1	2050-2150	1700	Slowly to 1600	1600-1650	Slowly and Uniformly	1-4 hr.	50° Max./hr.
2	2050-2150	1750	Slowly to 1600	1600-1650	Slowly and Uniformly	1-4 hr.	50° Max./hr.
3	2100-2200	1800	Slowly to 1600	1600-1650	Slowly and Uniformly	1-4 hr.	50° Max./hr.
4	2100-2200	1800	Slowly to 1600	1600-1650	Slowly and Uniformly	1-4 hr.	50° Max./hr.

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bDo not normalize these steels.

Annealing—Pack in a suitable container with mica dust or sand to which has been added approximately 1% of charcoal by weight. Heat to a temperature given in Table II and hold until the heat has thoroughly penetrated the mass. Cool in the furnace as slowly as possible.

Hardening

Preheating—Heat slowly and uniformly to a temperature of 1500-1600°F. Hold at this temperature until the steel is thoroughly heated through and transfer to the high temperature furnace. These steels decarburize readily if held too long at or above the preheating temperature.

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Where large tools are to be hardened, a double preheat is often desirable. The first preheating temperature is 1150-1300°F. and the second preheating temperature is 1600-1700°F.

High Heat—After being transferred to the high temperature furnace, steel No. 1 should be heated quickly to the hardening temperature of 2325-2375°F., while types No. 2, 3 and 4 should be heated to a hardening temperature given in Table III. As soon as the steel has reached this temperature it should be immediately quenched. Prolonged soaking will cause excessive decarburization and some grain growth.

Table III
Heat Treatments for Cobalt High Speed Steels

Steel No.	Preheat Temp. °F.	Hardening Temp. °F.	Quenching Medium	Tempering Temp. °F.
1	1500-1600	2325-2375	Oil, Air, Molten Bath	1000-1150
2	1500-1600	2350-2400	Oil, Air, Molten Bath	1000-1150
3	1500-1600	2325-2375	Oil, Air, Molten Bath	1000-1150
4	1500-1600	2325-2375	Oil, Air, Molten Bath	1000-1150

Quenching—These steels may be quenched in either still air, air blast, or oil, depending upon the size and design of the tool being hardened. They should be cooled to a temperature under 300, but not below 100°F. Unless equipment is available to keep the tools at a temperature within this range they should be tempered immediately. These steels also may be quenched in molten salt or lead maintained at a temperature of from 1000-1100°F. When quenched in a salt or lead bath the tool is allowed to remain in the bath for from 15-30 min., then removed and allowed to cool in still air. Tools treated in this manner are subject to the same tempering recommendations as when they are cooled in air or oil.

Tempering—To obtain maximum hardness, these steels should be tempered to 1050°F. and held at this temperature from 1-3 hr., depending on size. A second tempering, of from 600-650°F., will toughen these steels without materially affecting the initial hardness.

Surface Decarburization and Grinding—All cobalt high speed steels show a tendency to decarburize during the hardening operation in approximately direct proportion to the cobalt content. Because of this characteristic it is always advisable to grind the working surface of the steel after hardening. It is strongly recommended that the steel be ground after forging and annealing and before hardening to remove any decarburized surface that may have resulted from the forging heat. This precaution will lessen the amount of decarburization.

It is important that the proper grade and speed of wheel be used when grinding a hardened tool, since with too hard or fine a wheel or with too high speed there is pronounced danger of cracking in grinding. Wet grinding is not generally recommended but may be applied successfully with proper equipment. In dry grinding care must be taken not to dip tools into water to cool, because such practice will result in cracking or checking the tools.

Composition and Heat Treatment of Chisels*

(See Also the General Heat Treatment Article for Tool Steels, Page 987.)

General—Chisels must meet severe fatigue stresses and retain good cutting edges. Various steels as well as heat treatments are employed to meet these conditions. Only the principal steels and simpler treatments are given here.

Table I
Approximate Chemical Composition^a

Steel No.	C	Mn	Si	W	Cr	V	Mo
1	0.80						
2	0.80					0.20	
3	0.50				0.80	0.20	
4	0.60				0.50		
5	0.50			2.00	1.25	0.25	
6	0.55	0.80	2.00		0.50 Opt. (max.)	0.25 Opt. (max.)	0.30 Opt. (max.)
7	0.50	0.40	1.00			Opt.	0.50

^aThe analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Table II
Forging, Normalizing, and Annealing Chisels

Steel No.	Forging ^b			Normalizing After Forging ^c			Annealing ^c		
	Start °F.	Do not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15-60	1360-1400	Uniformly	1-4
2	1800-2000	1500	"	1600	"	15-60	1360-1400	"	1-4
3	1800-2000	1600	"	1650	"	15-60	1425-1450	"	1-4
4	1900-2100	1600	"	1600	"	15-60	1425-1450	"	1-4
5 ^a	1850-1950	1550	"	— Do not normalize —			1450-1500	"	1-4
6	1800-1950	1600	"	1600	Slowly	15-60	1450-1500	"	1-4
7	1800-1950	1600	"	1600	to 1450	15-60	1450-1500	"	1-4

^aAfter forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^cCooling rate of 50° max. per hr. to 1000°F.

Table III
Heat Treatments for Chisels

Steel No.	Rate of Heating For Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1		1450-1500		Brine or Water	300-550
2		1450-1500		Brine or Water	300-550
3	Slowly and Uniformly	1425-1450	1-4 hr.		
4	Slowly to 1400°F.	1450-1500	10 min.	Brine or Water	350-550
5	Slowly to 1400°F.	1650-1750	10-30 min.	Oil	350-650
6	Slowly to 1400°F.	1650-1750	10-30 min.	Oil	500-650
7	Slowly	1575-1675	10-30 min.	Brine or Water	350-700

Note—With pneumatic chisels various hardening methods are followed to put the shank in proper condition. Sometimes the chisel is treated as above and sometimes the shank is given a preliminary quench in oil from the temperatures given in Table III, after which the cutting edge is hardened as given in Table III, and the whole chisel tempered at the temperatures given.

Shank breakage can be minimized by quenching the tool all over and tempering the shank to a Brinell hardness of 450-500 for steels 1-4 and to 375-430 for steels 5-7.

Thumbnail cracks indicate that the steel was forged too cold. Fatigue failures can be minimized by eliminating decarburized surfaces and tool marks.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stots, Chairman; A. S. Jameson, A. J. Scheid, Jr., G. V. Luerssen, W. H. Wills, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadle, C. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

Composition and Heat Treatment of Cold Striking Dies for Silverware*

(See Also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the process to be followed in the heat treatment of cold striking dies for silverware when they are of the composition given in Table I. The base metal to be stamped may be steel, nickel-silver, or sterling silver.

During hubbing, steel work hardens to such an extent that it must be softened before the hubbing operations can be continued. To soften, the steel is packed and heated to 1250-1300°F., followed by slow cooling.

Table I
Approximate Composition of Striking Dies for Silverware*

Steel No.	C	Mn	V
1	0.90	0.30	0.20
2	1.10	0.30	0.20 Opt.

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Forging, Normalizing and Annealing—The temperatures for forging, normalizing, and annealing are given in Table II.

Table II
Forging, Normalizing, and Annealing Cold Striking Dies for Silverware

Steel No.	Forging ^a			Normalizing After Forging ^b			Annealing ^b		
	Start °F.	Do not Forge Below °F	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15-60	1360-1400	Slowly and Uniformly	1-4
2	1800-2000	1500	Slowly to 1450	1550-1650	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bCooling rate of 50° max. per hr. to 1000°F.

Hardening—To prevent scale from forming in the patterns, the dies are packed in suitable carbonaceous material. Great care should be employed in heating slowly to the hardening temperatures given in Table III. These temperatures are all well above the critical range, because experience has shown that such high heats produce materially better dies.

Table III
Heat Treatments for Cold Striking Dies for Silverware

Steel No.	Rate of Heating For Hardening	Hardening ^a Temp. °F.	Quenching Medium	Tempering ^b Temp. °F.
1	Slowly and Uniformly	1450-1500	Brine or Water	300-550
2	Slowly and Uniformly	1400-1500	Brine or Water	300-550

*When hardening, pack all dies in suitable carbonaceous material or place face down in a pan of carbonaceous material.

^bThe tempering temperature is governed largely by the metal to be worked and the pattern.

To obtain full and uniform hardness, the use of jets or sprays against the impression is recommended. Satisfactory dies can be obtained only by precise control of all operations.

Tempering—After quenching, the dies are tempered immediately at the tempering temperatures given in Table III. The hardness employed depends upon the metal to be struck and the pattern.

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Composition and Heat Treatment of Dies for Die Casting*

(See also the General Heat Treatment Article for Tool Steels, Page 987.)

Introduction—A die casting is made by forcing a molten or semimolten metal or alloy under pressure into a metallic mold or die. Little or no machining other than drilling for screws, bolts, and the removal of fins by dressing is required to put the casting in condition for use.

The essential feature in the die casting process which distinguishes it from other processes involving metallic molds, is that the fluid metal is forced into the die cavity by pressure. The pressure may be mechanical, as a plunger working in a cylinder, or air pressure.

Die castings are produced commercially from lead, tin, zinc, aluminum, magnesium, and copper-base alloys. Detailed information on the metals used for die castings will be found elsewhere in this Handbook.

General—Table I lists the steels generally used for die casting dies, with the treatments suggested for them, although it is recognized that other steels may be used.

The composition and heat treatment of steels used in die casting dies depend on the operating temperature. In dies for zinc and lead-base alloys (relatively low temperature work) carbon steels may be used without heat treatment. Aluminum and magnesium-base alloys require heat treated alloy steels; copper alloys (brass) require special steels and heat treatment. For die casting of zinc alloys, high grade "machinery steel" may be used, but certain low alloy steels are preferable, and for longest service the latter should be heat treated. Nitralloy is also used for zinc-base alloys.

Table I
Approximate Composition of Steels for Dies for Die Casting*

Steel No	C	Mn	Si	W	Cr	V	Mo	Ni
1	0.20-0.50							
	Used for Zn, Sn, and Pb base alloys—not heat treated.							
1A	0.50	0.80			0.90			
	Used for Zn, Sn, and Pb base alloys—used as normalized.							
2	0.45	0.70			0.80			1.25
	Used for Zn, Sn, and Pb base alloys—not heat treated for Pb and Sn, but sometimes heat treated for Zn.							
3	0.30	0.50			1.20		0.50 max.	Al-1.20
	Used for Zn, Pb base alloys—preferably in nitrided condition.							
4	0.45	0.60			2.25	0.20 Opt.		
	Used for some long run dies on Zn. Becoming obsolete for Al and Mg Heat treated.							
5	0.35		0.90	4.50	5.25	0.25 Opt.	0.50 Opt.	0.50 Opt.
	Used heat treated—used for Al and Mg base alloys but is giving way to No. 6 and No. 7. Co-0.50 Opt.							
6	0.30	0.60	0.90		5.00	0.25 Opt.	1.00	
	Used for Al and Mg base alloys—heat treated.							
7	0.30		0.90	1.00	5.00	0.25 Opt.	1.00	Co-0.50 Opt.
	Used for Al and Mg base alloys—heat treated.							
8	0.35			10.00	3.00	0.50		
	Used for Cu base alloys—heat treated.							

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Chemical Composition—The approximate chemical compositions of the steels generally used for die casting dies are given in Table I.

Normalizing and Annealing—Die casting die steels as received from the steel mills should be ready for machining. In case further forging must be done the steels should be annealed or normalized and annealed as recommended in Table II. Steels 4, 5, 6, 7, and 8 must be cooled slowly from forging by burying in lime, mica, ashes or similar heat insulating products to avoid strain cracks. Proper normalizing and annealing of these steels should follow this cooling process.

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Table II
Forging, Normalizing and Annealing for Dies for Die Castings

Steel No.	Forging ^c		Normalizing After Forging				Annealing ^d		
	Start °F.	Do Not Forge Below °F.	Rate of Heating, °F.	°F.	Rate of Heating	Time at Heat	Temp. °F.	Rate of Heating	Time at Heat
1	1800-2000	1500	Slowly to 1450	1500-1600	Slowly to 1450	15 min.-1 hr.	1360-1400	Slowly and Uniformly	1-4 hrs.
1A	1900-2100	1550	Slowly to 1450	1650	1 hr. per in.	$\frac{1}{2}$ heating time	1425-1450	Slowly and Uniformly	1-4 hrs.
2	1850-1950	1550	Slowly to 1450	1600	1 hr. per in.	$\frac{1}{2}$ heating time	1400-1450	1 hr. per in.	1-4 hrs.
3	1900-2100	1600	Slowly to 1450				See footnote ^b		
4 ^a	1900-2100	1600	Slowly to 1450	1700	1 hr. per in.	$\frac{1}{2}$ heating time	1425-1475	1 hr. per in.	$\frac{1}{2}$ total heating time
5 ^a	2000-2100	1650	Slowly to 1550		Do not normalize		1550-1600	1 hr per in.	$\frac{1}{2}$ total heating time
6 ^a	2000-2100	1650	Slowly to 1550		Do not normalize		1550-1600	1 hr per in.	$\frac{1}{2}$ total heating time
7 ^a	2000-2100	1650	Slowly to 1550		Do not normalize		1550-1600	1 hr. per in	$\frac{1}{2}$ total heating time
8 ^a	2050-2150	1650	Slowly to 1550		Do not normalize		1600-1650	1 hr per in.	1-4 hrs.

^aAfter forging cool slowly in lime or mica.

^bInstead of annealing, this steel is usually oil quenched from about 1750°F. and tempered at 1250-1350°F. This gives a Brinell hardness of approximately 200-250.

^cThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^dCooling rate of 50° max. per hr. to 1000°F.

^aAfter forging cool slowly in lime or mica.

Instead of annealing, this steel is usually oil quenched from about 1750°F. and tempered at 1250-1350°F. This gives a Brinell hardness of approximately 200-250.

^cThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^dCooling rate of 50° max. per hr. to 1000°F.

Packing for Hardening—It is usually desirable to pack harden dies which require temperatures above 1650°F. in order to prevent excessive scaling. Many die failures are caused from carburized or decarburized surfaces resulting from use of improper packing compounds. Carburization is probably the most dangerous and common result since carbonaceous materials are generally used.

Gray cast iron chips when new are carburizing in action at temperatures above 1650°F., but this action diminishes with use. Partially spent chips may be used at 1650-1700°F. Large, clean chips are preferable.

Aluminum oxide grain of 8-12 mesh size, has been tested and found safe for temperatures between 1750 and 2050°F. At the higher temperature a slight scale may form with this material which is usually not difficult to remove.

Pitch coke, 6-8 mesh size is highly satisfactory when properly prepared. It should first be placed in a pipe or box and heated to 2000°F. until all volatile matter has been removed. Double heating is recommended when high temperature packing is involved. This material has been used from 1700-2100°F. with safety. Below 1700°F. spent pitch coke is decarburizing in action.

In all cases the packing box should be well sealed to prevent access of furnace gases.

Rate of Heating for Hardening and Tempering—It should be remembered that the slower the heating the less the warping or change of size or shape. Therefore dies should not be heated faster than a rate that will give a total heating time of 1½ hr. per in. of greatest thickness of die plus packing material. Frequently it is necessary to heat more slowly than this, to hold distortion at a minimum.

Hardening and Tempering—Table III gives the temperature for hardening and tempering die casting dies. Dies should be tempered immediately after quenching. Tempering furnaces should be at approximately the temperature of the dies being put into them, to prevent too rapid or uneven heating. Dies should not be quenched from the tempering heat.

Tempering temperatures are generally regulated to produce a certain Brinell hardness which experience has shown to give the best results. Dies are frequently tempered on the low side of the range, the hardness tested, and then retempered at a slightly higher temperature if necessary, to produce the desired hardness. This method eliminates the chance of over tempering.

Table III
Heat Treatments for Dies for Die Casting

Steel No.	Preheat Temp., °F.	Rate of Heating for Hardening	Hardening Temp., °F.	Time at Heat	Quenching Medium ^c	Tempering ^{b,d} Temp., °F.
1		Not hardened				
1A		Not hardened				
2		1½ hr. per in. thickness ^a	1500-1550	1 hr./in.	Oil	500-800
3		See the article in this Handbook for instructions on nitriding.				
4			1600-1650 ^a		Oil	800-900
5		1½ hr. per in. thickness	1850-1950	1½ hr./in.	Still Air	1000-1100
6		1½ hr. per in. thickness	1800-1850	1½ hr./in.	Still Air	1000-1100
7		1½ hr. per in. thickness	1800-1850	1½ hr./in.	Still Air	1000-1100
8	1500-1650	Rapidly from Preheat similar to high speed	1850-2150	Do not soak	Air or Oil	1000-1250

^aUsually not treated when used for tin and lead. For zinc, treated dies last longer.

^bDies made from steels 4-8 are used at a working hardness of 402-460 Brinell.

^cDies quenched in oil should not be allowed to become completely cold in the oil. It is necessary to use judgment gained from experience to determine when to remove.

^dThe time at the tempering heat is 2 hr. per in. of greatest thickness, or even longer.

^eFor intricate dies, hold at this temperature for the full specified time, then drop the furnace temperature with the work to 1500°F. Hold until uniform, then quench as above.

Notes About the Process—When die casting aluminum or copper-base alloy castings, first heat the dies uniformly to a temperature of approximately 350°F. Dies for die casting may be given a protective coating before going into service. This coating depends upon the alloy being cast.

Composition and Heat Treatment of Cold Heading Dies*

(See also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the process to be followed in the heat treatment of cold heading dies for steels shown in Table I.

Table I
Approximate Composition of Steels for Cold Heading Dies^a

Steel No.	C	Mn	Cr	V
1	0.90	0.30	0.30 Max. Opt.	0.50 Max. Opt.
2	1.10	0.30	0.30 Max. Opt.	0.30 Max. Opt.

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Annealing for Strain Relieving—Dies and hammers that are cold hubbed should be heated to 1250-1350°F. and slowly cooled before hardening. If much metal is moved in hubbing, alternate annealing and hubbing operations are necessary.

Normalizing After Forging—If normalizing is necessary it should be done according to instructions in the article for the Heat Treatment of Carbon Tool Steel, page 991, and as given in Table II.

Table II
Forging, Normalizing, and Annealing Cold Heading Dies

Steel No.	Forging ^a			Normalizing After Forging ^c			Annealing ^b		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15-60	1360-1400	Slowly and Uniformly	1-4
2	1800-2000	1500	Slowly to 1450	1650	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bCooling rate of 50° max. per hr. to 1000°F.

Preheating and Hardening—In order to insure thorough heating and to lessen the time required in the hardening furnace, preheating is often advantageous. Preheating and hardening temperatures are shown in Table III.

Table III
Heat Treatments for Cold Heading Dies

Steel No.	Preheat Temp., °F.	Rate of Heating for Hardening	Hardening Temp., °F.	Quenching Medium	Tempering Temp., °F.
1	1000	Slowly and Uniformly	1500-1650 ^a	Brine or Water ^b	300-550
2	1000	"	1450-1600 ^a		300-550

*The size, shape and character of the impression will determine whether the high or low temperature is better for the die.

^bWhen quenching open dies without a jig, brine is preferable to water.

Tempering—Tempering should be started immediately after quenching. Time at temperature should not be less than one hour and longer periods are advisable.

The tempering temperature is governed by the type of die and the material to be headed. For extrusion dies, a minimum Rockwell hardness of C59 is usually necessary.

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Notes on Process—If difficulty from decarburized surfaces is experienced a light coating of boric acid during the heating period may be beneficial in overcoming the trouble. This coating is applied by quickly dipping the preheated die in a hot, saturated solution or by sprinkling the powder on the preheated die.

When hardening solid dies and hammers with deep impressions, it is essential to quench in a jig that forces the coolant, under pressure, into the impression or through the hole in such a way that the forming of all gas pockets is avoided and plenty of fresh coolant impinges against the surfaces to be hardened.

Solid dies of relatively small cross section are usually quenched through the hole only. Large dies may be immersed in the quenching solution while the coolant is forced under pressure through the hole.

When hardening open dies care must be taken to avoid gas pockets in the die impressions. This is best done by a jig that forces the quenching medium against the surface to be hardened.

In hardening heading dies it is essential that a uniform and sufficient depth of hardness be obtained to resist the tremendous pressures developed in the heading operation.

Composition and Heat Treatment of Roll Threading Dies*

(See also General Heat Treatment of Tool Steels, Page 987.)

General—This article covers the heat treatment of roll threading dies made from steels of the approximate compositions shown in Table I. In special cases steels of other compositions may be used but their treatment is not covered by this article.

Table I
Approximate Composition for Roll Threading Dies*

Steel No.	C	Mn	W	Cr	V	Mo
1	1.10					
2	1.10				0.20 Opt.	
3	0.90	1.10	0.50	0.50	0.20 Opt.	
4	0.90	1.60			Opt.	
5	1.15	0.30	1.60	0.50	0.20	
6	2.10			12.00		
7	1.50			12.00		0.75
8	0.70		18	4.00	1.00	

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Table II
Forging, Normalizing, and Annealing of Roll Threading Dies

Steel No.	Forging ^b			Normalizing After Forging ^c			Annealing ^a		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr
1	1800-2000	1500	Slowly to 1450	1550-1650	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4
2	1800-2000	1500	Slowly to 1450	1550-1650	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4
3	1800-1950	1600	Slowly to 1500	1650	Slowly to 1500	15-60	1425-1450	Slowly and Uniformly	1-4
4	1800-1900	1600	Slowly to 1500	1550	Slowly to 1500	15-60	1400-1425	Slowly and Uniformly	1-4
5	1800-1950	1600	Slowly to 1500	1700	Slowly to 1500	15-60	1450-1475	Slowly and Uniformly	1-4
6 ^a	1800-1900	1600	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4
7 ^a	1800-1950	1600	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4
8 ^a	2050-2150	1700	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4

^aAfter forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^cCooling rate 50° max. per hr. to 1000°F.

Forging and Heat Treatments Are Given in Tables II and III

In preparing the hot rolled annealed bars for the milling operation, it is essential that sufficient stock should be machined off to insure the removal of all surface defects and traces of decarburization. The steel must be of uniform hardness to prevent injury to the expensive milling hobs. After the thread form has been milled on the die face, all traces of oil and chips should be removed from the die before hardening.

*Prepared by the Subcommittee on Tool Steel. The membership of the subcommittee was as follows: N. I. Stotz, Chairman, A. S. Jameson, A. J. Scheidt, Jr., G. V. Luerssen, W. H. Wills, Burns George, J. E. Erb, P. J. McCarthy, F. F. McIntosh, J. H. McCadie, C. L. Harvey, H. T. Cousins, J. A. Succop, A. D. Beeken, Jr., J. P. Howley, H. A. Anderson and S. C. Spalding.

Strain Relieving—After machining a strain relieving anneal at 1100-1200°F. is often beneficial in preventing distortion in the teeth during subsequent heat treatment.

Hardening—In order to minimize distortion it is essential to heat all thread rolling dies slowly throughout the heating cycle. Remove from the quenching bath when the die temperature is reduced, to approximately 200°F. and transfer immediately to the tempering furnace.

Dies made from steels No. 6 and 7 are usually pack hardened or heated in atmosphere controlled furnaces to prevent decarburization. Pitch coke which has been heated to approximately 2000°F. to remove all volatile matter, or cast iron chips, may be used for the packing medium. The box should be heated slowly to 1250-1300°F. and held until a uniform temperature is reached throughout the box. The temperature should then be raised gradually to 1800-1825°F., and held until uniformity is reached in the charge. Remove the dies from the pack, brush free from adhering particles and air cool to room temperature.

Dies made from steel No. 8 are heated in a salt bath, controlled atmosphere furnace, or in a pack of pitch coke. This is necessary to preserve the thread form. In either case a hardening temperature lower than the optimum for 18-4-1 high speed steel when used as a cutting tool is recommended. Dies (steel No. 8) pack hardened in pitch coke should be heated slowly to 1450-1500°F. The container should then be transferred to a furnace heated to 2000-2050°F. As soon as the contents of the pot reaches this temperature the dies should be removed from the pack and oil quenched.

Tempering—Dies should be heated slowly to the temperature shown in Table III and held at temperature a minimum of two hours. Longer tempering times are advisable.

In general, a Rockwell hardness of C 57-59 is satisfactory.

Table III
Heat Treatments for Roll Threading Dies

Steel No.	Preheat Temp., °F	Rate of Heating for Hardening	Hardening Temp., °F.	Time at Heat	Quenching Medium	Tempering Temp., °F.
1		Slowly and Uniformly	1400-1475	15 min.	Brine or Water	300-550
2			1400-1500 ^b	15 min.	Brine or Water	300-550
3		Slowly to 1200	1450-1500	½ hr. for max. Hardness ^a	Oil	325-500
4		Slowly	1400-1475	No soak	Oil	325-500
5			1575-1825		Oil	350-550
6	1500	Very Slowly	1775-1825	15-45 min.	Oil	400-1000
7	1500	Very Slowly	1700-1800	15-45 min.	Oil	400-1000
8	1450-1600		2250-2350		Oil, Air or Molten Bath	1025-1150

^aDo not soak for minimum distortion.

^bThe carbon-vanadium type can be hardened from a higher temperature than the carbon steels.

Composition and Heat Treatment of Hot Forging Machine Tools*

(See Also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the procedure to be followed for the heat treatment of forging machine tools for hot work when of the composition given in Table I. It is not implied that these are the only suitable steels, but other steels may require different heat treatments.

Steel No. 1 is usually purchased in the heat treated condition and is machined

Table I
Approximate Composition of Hot Forging Machine Tools^a

Steel No.	Purpose	C	Mn	Si	W	Cr	V	Mo	Ni
1	Gripper dies, headers, piercers.....	0.60	0.80			0.75		0.25	1.50
2	Gripper dies, solid dies.....	0.60	0.65			0.90		0.75	2.00
3	Gripper dies, crowners; cut-offs.....	0.90				4.00			
4	Gripper dies	0.60				4.00		0.50	
5	Gripper dies, inserts, piercers,* punches,* headers	0.35		1.00	Opt.	5.00	0.40	1.40	
6	Gripper dies, header dies, solid dies, inserts, punches,* piercers*.....	0.35			10	3.00	0.50		
7	Header dies	0.80	0.30				Opt.		
8	Header dies	0.50				0.80	0.20		
9	Header dies, solid dies, inserts, piercers*	0.50			2.00	1.25	0.25		
10	Gripper dies, headers, solid dies, inserts	0.40	0.60	1.50	7.50	7.50			
11	Punches,* nut dies.....	0.50			18	4.00	1.00	Opt.	

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

*The words "punch" and "piercer" are often used interchangeably. In this article the word "punch" is applied to a tool that punches out a slug, thereby lessening the weight of the forging, whereas a piercer makes a hole without removing any metal from the forging and so not changing its weight.

Table II
Forging, Normalizing, and Annealing of Hot Forging Machine Tools

Steel No.	Forging ^b		Normalizing After Forging ^c			Annealing ^c		
	Start °F.	Dot Not Forge Below °F.	Rate of Heating, °F.	Rate of Heating °F.	Time at Heat	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1850-1950	1550		1600	Slowly to 1450	15-60 min.	1400-1450	Slowly and Uniformly
2	1850-1950	"		"	"	"	"	"
3 ^a	1850-1950	1600	Slowly to 1550	"	—Do not normalize—	1450-1500	"	1-4
4 ^a	1850-1950	"	"	"	"	"	"	"
5 ^a	2000-2100	1650	"	"	"	1500-1550	"	"
6 ^a	2050-2150	"	"	"	"	1600-1650	1 hr. per in.	"
7	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15-60 min.	1360-1400	Slowly and Uniformly
8	1800-2000	"	"	1850	"	"	1425-1450	"
9 ^a	1850-1950	1550	"	"	—Do not normalize—	1450-1500	Slowly and Uniformly	1-4
10 ^a	2000-2100	1700	Slowly to 1600	"	"	1600-1650	1 hr. per in.	"
11 ^a	2050-2150	"	"	"	"	"	1 hr./in. max. 1-4 thickness	"

^aAfter forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^cCooling rate 50° max. per hr. to 1000°F.

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and used without further treatment. Its life is usually shorter than the higher alloy steels, but the elimination of heat treatment and consequent movement in treating, after machining, is sometimes valuable.

Annealing—Heat to the temperature given in Table II. Hold at temperature for complete penetration of heat.

Preheating—Where preheating is specified in Table III, heat slowly and uniformly to the temperature given and transfer to the high heat furnace.

Table III-

Heat Treatments for Hot Forging Machine Tools

Steel No.	Preheat Temp. °F.	Rate of Heating for Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1		Slowly	1475-1550	10-30 min.	Oil	800-1100
2		"	1600-1650	"	Fan Blast	600-1000
3	1400-1500	"	1750-1825	"	Fan Blast	800-1100
4	1400-1500	"	1625-1800	"	Still Air	600-1100
5	1500-1550	"	1800	Do not soak	Still Air	1000-1200
6	1500-1550	Rapidly from preheat similar to high speed	1850-2150	Do not soak	Air or Oil	1000-1250
7		Slowly	1450-1500	10-30 min.	Brine or Water	300-550
8		Slowly and uniformly	1650-1750	10-30 min.	Oil	800-1100
9		Slowly to 1400°F.	1650-1750	10-30 min.	Oil	350-650 ^a
10	1500-1550	Slowly	2100-2150	Do not soak	Oil	1000-1250 ^b
11	1450-1600	Rapidly from preheat	2050-2100	" " "	Air	600
			2250-2350	" " "	Oil, Air	1000
					Molten Bath	1025-1150

^aFor low temperature work.

^bFor high temperature work.

Hardening—With Steel No. 5 heat as specified in the article for high speed steel on page 1000, but to the temperature recommended in Table III, and quench as soon as uniformly heated. All other steels should be heated slowly and uniformly throughout to the hardening temperature specified, and quenched when complete uniformity of heating is obtained.

Tempering—Heat slowly and uniformly to the temperatures given, holding at heat a minimum of 1 hr. per in. of thickness.

Composition and Heat Treatment of Die Blocks and Inserts*

(See also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the process to be followed in the heat treatment of die blocks and die inserts, such as are generally used in forging hammers.

To avoid annealing and rehardening of the dies after each operating service, many users purchase die blocks in the heat treated condition. This applies particularly to the larger sizes. Such dies are usually furnished with a uniformity of five points of scleroscope hardness, and in the hardness range of 40-60 scleroscope. Generally, the shallower the impression, the greater the hardness.

Composition—The approximate chemical compositions of carbon and alloy steel die blocks generally used are given in Table I.

Table I
Approximate Chemical Composition of Die Blocks*

Steel No.	Purpose	C	Mn	Cr	V	Mo	Ni
1	Hot forging	0.60	0.70				
2	Hot forging	0.70			0.25 Opt.		
3	Cold forging	0.85					
4	Drop hammer	0.60	0.70	1.00	Opt.		1.50
5	Drop hammer	0.60	0.70	0.90		0.20	
6	Drop hammer	0.60	0.80	0.75		0.25	1.50
7	Drop hammer	0.60	0.70	1.15	0.15	0.50	
8	Drop hammer	0.60	0.60	0.90	Opt.	0.70	1.75

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Annealing—The die blocks should be heated slowly and uniformly to the annealing temperature given in Table II.

Table II
Forging, Normalizing, and Annealing Die Blocks

Steel No.	Forging*			Normalizing After Forging			Annealing		
	Start °F.	Do not Forge Below °F.	Rate of Heat-ing	°F.	Rate of Heat-ing	Time at Heat, min.	Temp. °F.	Rate of Heat-ing	Time at Heat, hr.
1	1800-2000	1500	Slowly to 1450				1400-1450	Slowly and Uniformly	1-4
2	" "	"	"	1500-1600	1450	15-60	1360-1400	"	"
3	" "	"	"	1600	"	"	"	"	"
4	1850-1950	"	"	"	"	"	1400-1425	"	"
5	" "	1550	"	"	"	"	"	"	"
6	" "	"	"	1600	"	"	1400-1450	"	"
7	1900-2000	"	"	1650	"	"	1400-1425	Slowly and Uniformly	"
8	1850-1950	"	"	1600	"	"	"	"	"

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

Hardening—The die blocks should be warmed in front of the furnace to remove the chill, then charged into the furnace at not over 500°F. The heating time for hardening should be approximately 1 hr. for each in. of diameter or thickness and the time for holding at heat 1/5 for carbon and 2/5 for alloy steels of the time required to reach the hardening temperature. The hardening temperatures are given in Table III.

Carbon steel die blocks are quenched in water (not below 60°F.) and should be immersed face down to a depth of approximately 1 in. below the deepest impression.

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Table III
Heat Treatments for Die Blocks

Steel No.	Hardening Temp. °F.	Quenching Medium	Tempering Temp. °F.	Scleroscope Hardness	Brinell Hardness No.
1	1425-1475	Water	500-1000	50-70	352-512
2	1475-1525	"	"	"	"
3	1425-1500	"	350-600	70-80	512-600
4	1475-1550	Oil	600-1100	50-73	352-534
5	1475-1550	"	"	"	"
6	1475-1550	"	"	"	"
7	1500-1575	"	"	"	"
8	1575-1650	Air	"	"	"
	1500-1575	Oil	"	"	"

To develop full hardness a geyser of ample volume should be directed against the center of the die impression. Cool down to a temperature of approximately 450°F. or where reheating from the inside is not likely to occur to a sufficient degree to cause softening.

Die blocks that require oil quenching should be completely immersed, with the oil circulating well to give maximum heat dissipation. The volume of the oil bath should be ample so as to avoid an excessive rise in temperature. In case of large dies a strong oil geyser should be directed toward the center of the impression to obtain a uniform high hardness. The dies should be held beneath the surface of the oil until the steel has reached a temperature of approximately 450°F.

Tempering—After quenching the die blocks are tempered immediately at a temperature depending on the final hardness desired (Table III). Tempering may be done by placing the blocks shank down on a hot plate or in a furnace or bath. Blocks or inserts should not be charged in a furnace which is in excess of 400°F. or in a bath which is above 300°F. The heating time to temperature should not be less than 1 hr. per in. of least diameter or thickness and the holding time not less than 2/5 of the total heating time.

The approximate hardness to be expected with 0.60% carbon die blocks after tempering is as follows:

Tempering Temp., °F.	Scleroscope Hardness	Brinell Hardness No.
600	68	493
700	62	444
800	55	388
900	50	341
1000	43	285

Alloy steel die blocks maintain their hardness after tempering better than carbon steel and after tempering will test about 8 points scleroscope higher.

Die blocks for hot forging are rarely tempered below 600°F. Those used for cold work are tempered at lower temperatures, usually 350-600°F. as greater hardness is required.

Die Block Inserts—The term "insert" may refer to a die block (similar in composition and heat treated as such) used to form the entire forging. It frequently has less thickness than a regular die block because it is held in a die block holder. On the other hand, inserts usually refer to the small sections set into a die block in order to strengthen or minimize the wear at one or more points in the die block impression. These are generally made from a more expensive hot die steel and will last as long as the other portions of the impression, thus materially improving the life of the die block.

While hot die steel inserts may be made from a variety of types the more common steels are listed in Table IV and the heat treatments in Table V and VI.

Table IV
Approximate Composition of Hot Die Steels for Inserts*

Steel No.	C	W	Cr	V	Mo
1	0.50	2.00	1.25	0.25	
2	0.35	10	3.00	0.50	
3	0.50	18	4.00	1.00	Opt.

See footnote * in Table I.

Table V
Forging and Annealing for Hot Die Steels for Inserts

Steel No	Start °F.	Forging ^a	Rate of Heating	Annealing ^c			
		Do not Forge Below °F.		Temp. °F.	Rate of Heating	Time at Heat, hr.	Rate of Cooling
1 ^a	1850-1950	1550	Slowly to 1450	1450-1500	Slowly and Uniformly 1 hr. per in.	1-4	50°/hr. to 1000°F.
2 ^a	2050-2150	1650	Slowly to 1550	1600-1650	1 hr. per in. max. thickness	"	Max. 50°/hr. to 1000°F.
3 ^a	2050-2150	1700	Slowly to 1600	1600-1650	"	"	50°/hr. max. to 1000°F.

^aAfter forging cool slowly in lime or mica.

^bSee note ^a in Table II.

^cDo not normalize these steels.

Table VI
Heat Treatments for Hot Die Steels for Inserts

Steel No.	Preheat Temp. °F.	Rate of Heating For Hardening	Hardening Temp. ° F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1		Slowly to 1400	1650-1750	10-30 min.	Oil	350-650 ^a 1000-1250 ^b
2	1500-1550	{ Rapidly from Preheat } { similar to high speed }	1850-2150	Do not soak	Air or Oil	1000-1250
3	1500-1600		1900-2200		Oil, Air or Molten Bath	1025-1150

^aFor low temperature work.

^bFor high temperature work.

Notes About the Process

Protection of Surface of Die Blocks When Heating for Hardening—In order to reduce scale and decarburization it is recommended that dies be heated in a controlled atmosphere furnace or with the impression face packed in charcoal or spent pitch coke, Fig. 1.

Quenching—When quenching in water it is important not to allow the blocks to cool down too far. The temperature of approximately 450°F. may be determined by holding the head of a household match against the impression face of the block, which should not ignite the match for at least 15-20 sec. Instant ignition will indicate a temperature above 450°F.

To prevent warpage when quenching in water, the shank may be cooled to a black heat by pouring water on it.

When quenching in oil the blocks should be cooled to a temperature of 450°F. If the oil covering the block bursts into a voluminous yellow flame when the block is withdrawn the temperature of the block is too high and it must again be immersed until repeated trials give a blue flame slightly tinged with yellow.

When blocks or inserts are hardened in air, the blast should be dry and so directed as to strike the impression face uniformly. An air pressure of 12-24 oz. is suggested, with ample volume.

Tempering—Large carbon steel die blocks are sometimes tempered on a hot plate. When this method is used the die is placed shank down on a hot plate and heated until the desired color or scleroscopic hardness is obtained on the face. When testing the scleroscope hardness of a hot block it will read 4 or 5 points lower than if tested at room temperature. When relying upon temper color for hardness the following is suggested as a guide: Faint straw, 400°F.; straw, 440°F.; deep straw, 475°F.; bronze, 520°F.; peacock, 540°F.; full blue, 590°F.; light blue, 640°F.

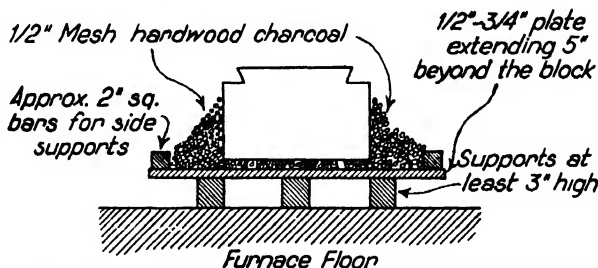


Fig. 1—Method of protecting surface of die block when heating for hardening.

Composition and Heat Treatment of Press Tools for Shearing, Blanking, and Punching*

(See also the General Heat Treatment Article on Tool Steels, Page 987.)

General—This article covers the heat treatment of blanking dies and punches when made from steels listed in Table I. Other steels less common than these may be used in practice, but they may have different heat treatments.

Table I
Approximate Chemical Composition^b

Steel No.	Purpose	C	Mn	Si	W	Cr	V	Mo
1	Cold work, dies and punches	0.85					Opt.	
2	Cold work, dies and punches	1.10					Opt.	
3	Cold work, dies and punches	0.90	1.10		0.50	0.50	0.20 Opt.	
4	Cold work, dies and punches	0.90	1.60					
5	Cold work, dies and punches	1.15	0.30		1.60	0.50	0.20	
6	Cold work, punches.....	0.50			2.00	1.25	0.25	
7	Cold work, punches.....	0.55	0.80	2.00		0.50 max. (Opt.)	0.25 max. (Opt.)	0.30 max. (Opt.)
8	Cold work, punches.....	0.50	0.40	1.00				0.50
9	Hot work, dies and punches.	0.35			10.00	3.00	0.50	
10 ^a	Cold work, dies and punches	0.70			18.00	4.00	1.00	
11	Hot work, punches.....	0.40	0.60	1.50	7.50	7.50		
12	Cold work, dies and punches	2.10				12.00		
13	Cold work, dies and punches	1.50				12.00		0.75

*The carbon content may be lower for special purposes.

^bThe analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analyses of any steel from these averages, the more the treatment may differ from that recommended.

Table II
Forging, Normalizing and Annealing Press Tools

Steel No.	Forging ^b			Normalizing After Forging			Annealing		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1700-2000	1500	Slowly to 1450°F.	1500-1650	Slowly to 1450°F.	15-60	1400-1425	Slowly and Uniformly	1-4
2	1700-2000	1500	Slowly to 1450°F.	1500-1650	Slowly to 1450°F.	15-60	1400-1425	Slowly and Uniformly	1-4
3	1800-1950	1600	Slowly to 1500°F.	1650	Slowly to 1500°F.	15-60	1425-1450	Slowly and Uniformly	1-4
4	1800-1900	1600	Slowly to 1500°F.	1550	Slowly to 1500°F.	15-60	1400-1425	Slowly and Uniformly	1-4
5	1800-1950	1600	Slowly to 1500°F.	1700	Slowly to 1500°F.	15-60	1450-1475	Slowly and Uniformly	1-4
6	1850-1950	1550	Slowly to 1450°F.	Do not normalize			1450-1500	Slowly and Uniformly	1-4
7	1800-1950	1600	Slowly to 1450°F.	1600	Slowly to 1450°F.	15-60	1450-1500	Slowly and Uniformly	1-4
8	1800-1950	1600	Slowly to 1450°F.	1600	Slowly to 1450°F.	15-60	1450-1500	Slowly and Uniformly	1-4
9 ^a	2050-2150	1650	Slowly to 1550°F.	Do not normalize			1600-1650	1 hr. per in. max. thick.	1-4
10 ^a	2050-2150	1700	Slowly to 1600°F.	Do not normalize			1600-1650	1 hr. per in. max. thick.	1-4
11 ^a	2000-2100	1700	Slowly to 1600°F.	Do not normalize			1600-1650	1 hr. per in. max. thick.	1-4
12 ^a	1800-1900	1600	Slowly to 1600°F.	Do not normalize			1600-1650	1 hr. per in. max. thick.	1-4
13 ^a	1800-1950	1600	Slowly to 1600°F.	Do not normalize			1600-1650	1 hr. per in. max. thick.	1-4

*After forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

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Approximate Chemical Composition—The approximate chemical composition of the steels generally used for blanking dies are given in Table I.

Forging, Normalizing, and Annealing—The temperatures for these operations are given in Table II. Special instructions as to procedures may be noted in the "General Recommendations for the Heat Treatment of Tool Steels" or under special articles for the various types of steels under consideration.

Heat Treatment—The heat treatments are given in Table III.

Table III
Heat Treatments for Press Tools for Shearing, Blanking and Punching

Steel No.	Preheat Temp., °F.	Rate of Heating for Hardening	Hardening Temp., °F.	Time at Heat	Quenching Medium	Tempering Temp., °F.
1	....	Slowly	1400-1450	10-30 min.	Brine or Water	350-550
2	....	Slowly	1400-1475	10-30 min.	Brine or Water	350-550
3	1200	Very Slowly	1450-1500	Footnote ^a	Oil	325-500
4	1200	Very Slowly	1400-1475	Do not soak	Oil	325-500
5	1300	Very Slowly	1575-1625	Footnote ^a	Oil	350-550
6	....	Slowly to 1400	1650-1750	10-30 min.	Oil	500-650
7	....	Slowly	1575-1675	10-30 min.	Brine or Water	350-700
8	....	Slowly	1525-1575	10-30 min.	Brine or Water	350-700
9	1500-1550	Rapidly from Preheat —similar to high speed	1850-2150	Do not soak	Air or Oil	1000-1250
10	1450-1600	Rapidly from Preheat	2200-2300 ^b	Do not soak	Air or Oil	1050-1200
	1450-1600		1950-2200 ^c	See footnote ^c	Air or Oil	1050-1200
	1450-1600		1850-2000 ^c	See footnote ^c	Oil	500-900
11	1500-1550	Rapidly from Preheat	2100-2150	Do not soak	Air or Oil	1100-1250
12	1500	Very Slowly	1775-1825	15-45 min.	Oil	400-1000
13	1500	Very Slowly	1800-1875	15-45 min.	Still Air	400-1000
			1700-1800	15-45 min.	Oil	400-1000

^aTo obtain max. hardness hold at heat up to ½ hr. For minimum change in dimension do not hold at heat.

^bHeat treatment for cold work.

^cHeat treatment for pack hardening. Burned pitch coke has been found best adapted for the packing material. Carburizing compounds should not be used. Care must be used in this process that the steel does not become too highly carburized. Too high a carbon concentration on the surface will cause spalling or even an actual fusion of the surface of the die during hardening. Do not hold longer than is necessary to assure that the die has reached the desired temperature.

Notes About the Process—In most cases both the punch and the die are made from the same steel. For dies of intricate design or when distortion is a factor, an air or oil hardening steel should be used, but for more simple designs a water hardening steel may be used.

Preheating of steels 3 and 4 may be done without the use of two furnaces by heating slowly and uniformly to 1200°F. and then heating more rapidly to the hardening temperature. A slow and uniform preheating is helpful in preventing distortion.

Where pack hardening is suggested refer for instructions to the general article on the Heat Treatment of Tool Steels in this Handbook.

Steels 12 and 13 absorb heat at a slower rate than the other steels. They should therefore be heated much more slowly. These steels are sometimes pack hardened, especially if the die will not permit grinding.

Composition and Heat Treatment of Solid Shear Blades*

(See also the General Heat Treatment for Tool Steels, Page 987.)

General—This article covers the heat treatment of solid shear blades and the steels most generally used for hot and cold shearing.

Chemical Composition—The approximate chemical composition of the steels generally used for solid shear blades is given in Table I.

Table I
Approximate Chemical Composition^a

Steel No.	Purpose	C	Mn	Si	W	Cr	V	Mo
1	Cold shearing heavy material	0.85					0.30 Opt.	
2 ^b	Cold shearing light and medium material	1.00	0.35				0.30 Opt.	
3	Cold shearing heavy and medium material	0.55	0.80	2.00		0.50 Opt. (max.)	0.25 Opt. (max.)	0.30 Opt. (max.)
4	Cold shearing light material	0.50	0.40	1.00				0.50
5	Cold shearing heavy and medium material	0.70	0.30			0.90	0.20	
6	Hot and cold shearing of medium or heavy material	0.60	0.60			1.00	Opt.	0.50
7	Warm or cold shearing of medium or heavy material	0.50			2.00	1.25	0.25	Ni 1.50
8	Hot shearing	0.35			10.00	3.00	0.50	
9	Cold shearing light material	0.70			18.00	4.00	1.00	
10 ^a	Cold shearing light material	2.10				12.00	1.00	
11 ^a	Cold shearing light and medium material	1.50				12.00		0.75

^aSteels 10 and 11 may contain optional amounts of V, Ni or Co. With lower carbon content steel No. 11 can be used for hot shearing up to red temperatures.

^bLight shearing means stock up to ¼ in. in dia. or thickness; medium shearing over ¼-¾ in.; and heavy shearing, over ¾ in.

^cThe analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Forging—Heat slowly and uniformly to the temperatures given in Table II. The higher range of temperature refers to large masses subject to heavy reductions and the lower range refers to small masses or light reductions. Forging should be finished as near to but not under the limit indicated. Intermediate or highly alloyed steels should be given retarded cooling after forging, preferably by covering with lime or mica.

Normalizing—For most grades normalizing from the temperatures shown in Table II is recommended.

Annealing—After forging and normalizing, or when resizing a finished blade, heat the steel thoroughly to the temperatures shown in Table II. Soak at heat from 1-4 hr. and cool slowly in the furnace.

Hardening—Heat slowly and uniformly to the temperatures shown in Table III. Quench as directed.

When quenching heavy and long shear blades, it is recommended that the bath be agitated and that the knives be quenched with the edge down rather than the flat and that the knife be turned over during the quench to minimize warpage.

Tempering—Use the temperatures given in Table III. In general it is best to hold at the tempering heat for a minimum of 2 hr. The hardness of the shear

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blades is governed by the type of material to be sheared and the character of the work to which the shears are to be subjected. For shearing thin material, the scleroscope hardness should be on the high side.

Notes About the Process—Shear blades should be straightened, when quenching, on the descending heat. A straightening machine, such as a hydraulic press, with knife edge supports, should be available in order to apply a quick uniform pressure

Table II
Forging, Normalizing and Annealing of Solid Shear Blades

Steel No.	Forging ^a			Normalizing After Forging			Annealing ^c		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.
1	1800-2000	1500	Slowly to 1450°F.	1800	Slowly to 1450	15-60	1360-1400	Slowly and Uniformly	1-4
2	1800-2000	1500	Slowly to 1450	1500-1850	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4
3	1800-1950	1600	Slowly to 1450	1600	Slowly to 1450	15-60	1450-1500	Slowly and Uniformly	1-4
4	1800-1950	1600	Slowly to 1450	1600	Slowly to 1450	15-60	1450-1500	Slowly and Uniformly	1-4
5	1800-1950	1550	Slowly to 1450	1600	Slowly to 1450	15-60	1425-1450	Slowly and Uniformly	1-4
6	1850-1950	1550	Slowly to 1450	1550-1625	Slowly to 1450	15-60	1400-1425	Slowly and Uniformly	1-4
7 ^a	1850-1950	1550	Slowly to 1450	Do not normalize			1450-1500	Slowly and Uniformly	1-4
8 ^a	2050-2150	1650	Slowly to 1550	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4
9 ^a	2050-2150	1700	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4
10 ^a	1800-1900	1600	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4
11 ^a	1800-1950	1600	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4

^aAfter forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^cCooling rate 50°F. max. per hr. to 1000°F.

Table III
Heat Treatments for Solid Shear Blades

Steel No.	Preheat Temp., °F.	Rate of Heating for Hardening	Hardening Temp., °F.	Time at Heat	Quenching Medium	Tempering Temp., °F.
1		Slowly and Uniformly	1450-1500	15 min.-1 hr.	Brine or Water	300-550
2		Slowly and Uniformly	1400-1500	15 min.-1 hr.	Brine or Water	300-550
3		Slowly and Uniformly	1550-1650	15 min.-1 hr.	Brine or Water	300-550
4		Slowly and Uniformly	1625-1875	15 min.-1 hr.	Brine or Water	300-550
5		Slowly and Uniformly	1450-1500	15 min.-1 hr.	Brine or Water	300-550
6			1550-1625		Oil	600-1000
7		Slowly to 1400	1650-1750	10-30 min.	Oil	350-650 ^a
8	1500-1550	Rapidly from Preheat similar to high speed	1850-2150	Do not soak	Air or Oil	1000-1250 ^b
9	1450-1600		2250-2350		Oil, Air or Molten Bath	1025-1150
10	1500	Very slowly	1725-1825	15-45 min.	Oil	400-1000
11	1500	Very slowly	1800-1900	15-45 min.	Air	400-1000

^aFor low temperature work. ^bFor high temperature work.

at the desired locations along the knife. For straightening on the descending heat, the shear blades should be withdrawn from the bath at a temperature from 400-600°F., which is just below the point where the oil ceases to flash, or in the case of water quenched blades, just where the water steams or dries off the blades immediately. When it is necessary to straighten after tempering, this should be done as soon as possible while the full tempering heat remains in the shear blade.

Care should be exercised in the selection of an alloy steel for heavy and extra heavy shearing, as deep hardening steels frequently fail by spalling on the cutting edge or by cracking across the blade.

Composition and Heat Treatment of Rivet Sets for Hot Work*

(See also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article deals with two types of rivet dies: (1) Pneumatic rivet sets used in air guns, and (2) compression rivet dies which head by pressure rather than blows. The approximate chemical compositions of the steels generally used for both types of rivet dies are given in Tables I and IV.

Table I
Approximate Chemical Composition for Pneumatic Rivet Sets*

Steel No.	C	Mn	Si	W	Cr	V	Mo
1	0.80	0.35 max.					
2	0.80	0.30				0.20	
3	0.50				0.80	0.20	
4	0.50	0.75		2.00	1.25	0.20	
5	0.55	0.80	2.00		0.50 Opt. (max.)	0.25 Opt. (max.)	0.30 Opt. (max.)
6	0.50	0.40	1.00			Opt.	0.50

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Table II
Forging, Normalizing, and Annealing for Pneumatic Rivet Sets

Steel No.	Forging ^a			Normalizing After Forging			Annealing ^b		
	Start °F.	No Forge Below °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat	Temp. °F.	Rate of Heating	Time at Heat
1	1800-2000	1500	Slowly to 1450	1500-1600	Slowly to 1450	15 min.-1 hr.	1360-1400	Slowly and Uniformly	1-4 hrs
2	1800-2000	1500	Slowly to 1450	1600	Slowly to 1450	15 min.-1 hr.	1360-1400	Slowly and Uniformly	1-4 hrs
3	1800-2000	1500	Slowly to 1450	1650	Slowly to 1450	15 min.-1 hr.	1425-1450	Slowly and Uniformly	1-4 hrs
4	1900-1700			Do not normalize			1450-1475		
5	1800-1950	1600	Slowly to 1450	1600	Slowly to 1450	15 min.-1 hr.	1450-1500	Slowly and Uniformly	1-4 hrs
6	1800-1950	1600	Slowly to 1450	1600	Slowly to 1450	15 min.-1 hr.	1450-1500	Slowly and Uniformly	1-4 hrs

*The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^bCooling rate 50° max. per hr. to 1000°F.

Table III
Heat Treatments for Pneumatic Rivet Sets

Steel No.	Rate of Heating for Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1	Slowly and Uniformly	1450-1500	15 min.	Brine or Water ^a	300-550
2	Slowly and Uniformly	1450-1500	15 min.	Brine or Water ^a	300-550
3	Slowly and Uniformly	{1425-1450 1550-1600 1650-1750	15 min. 15 min. 15 min.	Brine or Water Oil Oil ^b	300-550 300-550 450-600
4	Slowly and Uniformly	{1550-1600 1550-1650	15 min. 15 min.	Water Water ^c	450-600 600-800
5	Slowly and Uniformly	1525-1575	15 min.	Brine or Water	550-750

^aA 10% brine solution is used.

^bFor this treatment, oil is the preferred quenching medium.

^cIf this steel contains around 0.50% molybdenum, it may be quenched in oil by using a temperature approximately 25-50°F. higher than the temperature for water quenching.

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Quenching and Tempering—It is recommended that the rivet sets should be completely immersed while a gentle stream of the quenching medium is being forced into the cup. When quenching, it is good practice to hold the rivet set with a special pair of tongs to keep the water away from the ring, but which at the same time permits uniform cooling of the cup and shank.

The sets should be tempered all over at the temperatures given in Tables III and VI.

Table IV
Approximate Chemical Composition of Steel for Rivet Dies for Hot Pressing^a

Steel No.	C	W	Cr	V
1	0.90		4.00	
2	0.50	2.00	1.25	0.25
3	0.35	10.00	3.00	0.50

^aSee Footnote ^a in Table I.

Table V
Forging and Annealing for Rivet Dies for Hot Pressing

Steel No.	Start °F.	Forging ^b Do not Forge Below °F.	Rate of Heating	Temp. °F.	Annealing ^c Rate of Heating	Time at Heat	Rate of Cooling
1 ^a	1850-1950	1600	Slowly to 1550	1450-1500	1 hr. per in. max. thickness	1-4 hrs.	Max. 50° per hr. to 1000°F.
2 ^a	1850-1950	1550	Slowly to 1450	1450-1500	Slowly and Uniformly	1-4 hrs.	Max. 50° per hr. to 1000°F.
3 ^a	2050-2150	1650	Slowly to 1550	1600-1650	1 hr. per in. max. thickness	1-4 hrs.	Max. 50° per hr. to 1000°F.

^aAfter forging cool slowly in lime or mica.

^bSee footnote ^a in Table II.

^cDo not normalize these steels.

Table VI
Heat Treatments for Rivet Dies for Hot Pressing

Steel No.	Preheat Temp. °F.	Rate of heating for Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1		Slowly and Uniformly	1750-1850	15 min.	Air ^a	950-1100 ^b
2		Slowly to 1400	1650-1750	10-30 min.	Oil	900-1100
3	1500-1550	Rapidly from Preheat similar to high speed	1850-2150	Do not soak	Air or Oil	1000-1250

^aQuench in low pressure air blast or still air.

^bThis tempering range is for dies quenched in air blast. When cooled in still air the dies are usually not tempered.

Composition and Heat Treatment of Taps and Other Thread Cutting Tools*

(See also the General Heat Treatment Article for Tool Steels, Page 987.)

General—This article covers the process to be followed in the heat treatment of taps and other thread cutting tools when made from the steels listed in Table I.

Table I
Approximate Chemical Composition for Taps and Thread Cutting Tools^b

Steel No.	C	Mn	W	Cr	V
1 ^a	1.15	0.30	1.60	0.50	0.20
2	1.15				
3	0.70		18.00	4.00	1.00

^aThis steel is available with optional percentages of Cr or V, either singly or in combination.

^bThe analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

Annealing—Place the steel in the furnace and heat slowly and uniformly to the temperature given in Table II. Hold at temperature for sufficient time to obtain complete penetration of heat. It is recommended that the steel should be protected from furnace gases when heating and cooling. After properly heating, cool slowly in the furnace.

Table II
Forging, Normalizing and Annealing of Taps and Other Thread Cutting Tools

Steel No.	Forging ^a			Normalizing After Forging ^c			Annealing ^a		
	Start °F.	Do Not Forge Below °F.	Rate of Heating	F.	Rate of Heating	Time at Heat, min	Temp. °F.	Rate of Heating	Time at Heat
1	1800-1950	1600	Slowly to 1500	1700	Slowly to 1500	15-60	1450-1475 ^b	Slowly and Uniformly	1-4 hr.
2	1800-2000	1500	Slowly to 1450	1800	Slowly to 1450	15-60	1400-1440	Slowly and Uniformly	1-4 hr.
3 ^c	2050-2150	1700	Slowly to 1600	Do not normalize			1600-1650	1 hr. per in. max. thickness	1-4 hr.

^bIf lead or salt bath is used for heating, cool in lime, mica, or infusorial earth.

^cAfter forging cool slowly in lime or mica.

^dThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

^eCooling rate 50° max. per hr. to 1000°F.

Packing—For instructions on packing refer to the general article on the Heat Treatment of Tool Steels in this Handbook.

Hardening—Steels 1 and 2 are frequently heated in salt or lead baths. When this practice is followed a quenching temperature approximately 25°F. higher than that recommended for furnace heating is necessary. The tools should be preheated before immersion in the bath and should be withdrawn from the quenching medium when cooled to 200°F.

Maintenance of thread form and prevention of excessive lead change is more difficult with tools made from steel No. 3. Controlled atmosphere furnaces or salt baths are beneficial. When using controlled atmosphere furnaces a high CO content with low moisture and CO₂ is suggested. If semimuffle type furnaces are used a large excess of gas should be maintained and the tools removed for quenching as

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soon as the temperature in Table III is reached. The operation should be guided by the temperature of the threads.

Tempering—After quenching, reheat immediately in oil, salt, or furnace for the time and temperature specified in Table III.

Table III
Heat Treatments for Taps and Other Thread Cutting Tools

Steel No.	Preheat Temp., °F.	Rate of Heating for Hardening	Hardening Temp., °F.	Quenching Medium	Tempering Temp., °F.
1		Slowly and Uniformly	1575-1625 ^a	Oil	350-550
2		Slowly and Uniformly	1400-1475 ^b	Brine or Water	300-550
3	1450-1600	Slowly and Uniformly	2250-2350 ^c	Oil, Air or Molten Bath	1025-1150

^aIf a lead bath is used for heating, a higher temperature and shorter time at heat may be used.

^bHold shortest time possible to thoroughly heat through.

^cWhen heating in fused salts or controlled atmosphere furnaces, the hardening temperature is generally 2275-2350°F.

Notes About the Process—It is assumed that the tap shanks are below the hardening temperature and are not fully hardened. If the shanks have been fully hardened they must be tempered in order to toughen them, especially the smaller sizes. Acme style threads as well as modified or coarse pitch threads should be tempered at the higher temperatures.

Composition and Heat Treatment of Steels for Plastic Molds*

(See also the General Article on Heat Treatment for Tool Steels, Page 987.)

General—This article covers the steels and their treatments for plastic molds, but may not include all types of steels used for this work.

Plastic materials are those derived from phenol, urea, rubber, casein, and other bases, and are molded in steel molds under pressure and usually with heat. Since the molded article depends upon the character of the cavity in the mold not only for its shape, but for the perfection of its finish as well, it is necessary that mold steels be of high quality with regard to cleanness and response to heat treatment.

The mold cavities are formed either by hubbing or by cutting. The operation of hubbing consists of sinking the impression cold with a master hub. Since die steels which are to be hubbed must be annealed quite soft, they are usually of the carburizing type.

Where the conditions are such that the hubbing steels cannot be used the dies are machine cut.

Requirements of Mold Steels—From the foregoing it is obvious that a good mold steel should have the following properties: 1. Cleanness; 2. Ease of fabrication in hubbing, machining, and heat treating; and 3. Strength to resist deformation in service, and wear resistance.

Cleanness—It is desirable that the steel be free from internal defects which might appear on the surface of the cavity and mar the finish of the product. Under operating pressures and temperatures, these internal defects tend to open and leave ridges or imperfections on the surface of the work. The hot acid etch test as described elsewhere in this Handbook is therefore recommended for the inspection of steel for plastic molds.

Table I
Approximate Composition for Molds and Hubs*

Steel No.	Purpose	C	Mn	W	Cr	Mo	Ni	Annealed, Brinell Hardness, max.
<i>Steels Used for Molding</i>								
1	Hubbing	0.05	0.15					100
2	"	0.10	0.20		0.60		1.25	125
3	Cut die and hubbing	0.15	0.45		1.50		3.50	150
4	"	0.15	0.45			0.30	1.50	150
5	Cut die	0.40	0.45		1.50		3.50	200
6	"	0.90	1.60					200
7	"	0.90	1.10	0.50	0.50			200
8	"	1.50			12.00	0.75		230
<i>Steels Used for Hubs</i>								
9	Hubs*	0.50	0.40		0.80	0.75	1.50	200
10	Hubs	0.90	1.10	0.50	0.50			200
11	"	1.50			12.00	0.75		230

*The analyses given are type analyses only. Actual analyses of the steels they represent will, of course, vary from these averages a reasonable amount. It should be remembered that the greater the variation in analysis of any steel from these averages, the more the treatment may differ from that recommended.

*There are many types of tool steel used for hubs. The steels described here are only meant to be typical examples.

Ease of Fabrication in Hubbing, Machining, and Heat Treating—Some molds are shaped largely by hubbing, some by machining and others by a combination of both. The depth to which a hub can be driven in, as well as the power needed for the operation, depends largely upon the hardness of the mold steel when annealed. This in turn depends upon analysis; a steel containing no alloys can be annealed considerably softer than an alloy steel of the same carbon content. Consequently the easy hubbing steels do not generally make as strong a mold as

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those which are more difficult to hub. The selection of the steel will therefore be a compromise between final strength and wear resistance and hubbing properties.

Easy and clean machining properties are desirable in mold steels that must be machined to shape. Since cleanness is an important factor the high sulphur types are not desirable, and careful annealing must therefore be depended upon to produce the required machining properties.

In heat treating there are three factors which must be carefully watched in addition to the usual requirements, namely distortion, scaling and soft spots. All three are very undesirable.

Strength and Wear Resistance—The question of strength is vital in dies having thin sections, or in large dies where an entire surface may sink under heat and pressure. In the latter instance when a case hardening steel is used, core hardness is of considerable importance.

Wear resistance is of importance on long run dies, and is greatly improved by the addition of alloys.

Steel Compositions and Treatments—Table I shows average analyses of a number of die steels used in plastic molds. Included are several tool steels used in making the hubs. Tables II and III give the heat treatment for these steels. Since it is sometimes necessary in the hubbing of deep impressions to reanneal between operations, this table also covers annealing treatments.

Details of Four Steels—The type of steel selected will depend upon a number of factors involved in the particular application. The entire field can usually be covered by four steels, namely No. 1, 2, 3 and 6 in Table I.

Table II
Forging, Normalizing and Annealing Molds and Hubs

Steel No.	Forging ^b Do not Forge Below			Normalizing After Forging			Annealing			
	Start °F.	Rate of Heating	°F.	Rate of Heating	Time at Heat, min.	Temp. °F.	Rate of Heating	Time at Heat, hr.	Rate of Cooling	
1	1700-2000	1400	Slowly	1600	Slowly	15-60	1525-1550	Slowly and Uniformly	1-4	Slowly
2	1700-2000	1500	Slowly	1550	Slowly	15-60	1475-1500	Slowly and Uniformly	1-4	Slowly
3	1700-2000	1500	Slowly	1550	Slowly	15-60	1450-1475	Slowly and Uniformly	1-4	Slowly
4	1700-2000	1500	Slowly	1550	Slowly	15-60	1450-1475	Slowly and Uniformly	1-4	Slowly
5	1700-2000	1500	Slowly	1550	Slowly	15-60	1425-1450	Slowly and Uniformly	1-4	Slowly
6	1800-1900	1600	Slowly to 1500	1550	Slowly to 1500	15-60	1400-1425	Slowly and Uniformly	1-4	Max. 50°/hr. to 1000°F.
7	1800-1950	1600	Slowly to 1500	1650	Slowly to 1500	15-60	1425-1450	Slowly and Uniformly	1-4	Max. 50°/hr. to 1000°F.
8*	1800-1950	1600	Slowly to 1600	Do not normalize		1600-1650	1 hr. per in.	1-4	Max. 50°/hr. to 1000°F.	Slowly
9	1700-2000	1500	Slowly	1550	Slowly	15-60	1425-1450	Slowly and Uniformly	1-4	Max. 50°/hr. to 1000°F.
10	1800-1950	1600	Slowly to 1500	1550	Slowly to 1500	15-60	1400-1425	Slowly and Uniformly	1-4	Max. 50°/hr. to 1000°F.
11*	1800-1950	1600	Slowly to 1600	Do not normalize		1600-1650	1 hr. per in.	1-4	Max. 50°/hr. to 1000°F.	Slowly

*After forging cool slowly in lime or mica.

^bThe temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions.

Steel No. 1 is suitable for the manufacture of intricately shaped molds where ease of hubbing is of primary importance. It can also be used to advantage where only short runs are needed. Since the steel can be annealed to 100 Brinell it will permit a large amount of hubbing. For the same reason it is somewhat difficult to machine, although the machining properties are considerably improved when severely worked by partial cold hubbing.

Since this steel is a carburizing type with a relatively soft core extremely high pressures are not possible. For short runs, dies may be cyanided rather than carburized.

Steel 2 is a good general purpose mold steel, applicable to the manufacture of practically all classes of molds. While not quite so easy to hub as steel No. 1 still

its hubbing properties can be made satisfactory by proper annealing. It has the advantage of greater core strength, greater case strength, and greater wear resistance. It can be machined without great difficulty and can be hardened uniformly without danger of soft spots when quenched in either brine or oil.

Steel No. 3 (as well as 4) is adapted to the manufacture of large dies and for dies where maximum strength and length of service are required. While this steel is included under the steels for cut dies some hubbing operations are possible. With proper annealing it can be made to machine quite freely. It has the advantage of an extremely high core strength to withstand heavy loads even in large sections without cracking of the mold surface. It is excellent for wear resistance. It is capable of carburizing and heat treatment with no danger of soft spots.

Table III
Heat Treatments for Molds and Hubs

Steel No.	Carburizing °F.	Preheat Temp. °F.	Rate of Heating for Hardening	Hardening Temp. °F.	Time at Heat	Quenching Medium	Tempering Temp. °F.
1	1700		1½ hr. per in.	1450-1475	15 min.	Brine or Water	300-400
2	1700		1½ hr. per in.	1450-1475	15 min.	Brine or Water	300-400
3	1700		1½ hr. per in.	1400-1425	15 min.	Oil	300-400
4	1700		1½ hr. per in.	1400-1425	15 min.	Oil	300-400
5			1½ hr. per in.	1600-1625	15 min.	Air	300-350
6			1½ hr. per in.	1400-1475	Do not soak	Oil	325-500
7			1½ hr. per in.	1450-1500	Soak for hardness up to ½ hr. For min. change don't soak	Oil	325-500
8		1500	1½ hr. per in.	1700-1800	15-45 min.	Oil	400-1000
				1800-1900	15-45 min.	Air	400-1000
9			1½ hr. per in.	1700-1750	15 min.	Oil	400-500
10			1½ hr. per in.	1450-1500	Soak for hardness up to ½ hr. For min. change don't soak	Oil	325-500
11		1500	1½ hr. per in.	1700-1800	15-45 min.	Oil	400-1000
				1800-1900	15-45 min.	Air	400-1000

Steels No. 6 and 7 are used when it is not desirable to carburize. Hubbing is not recommended. Strength and wear resistance are excellent. These steels have the advantage of uniform hardness and freedom from size change in hardening.



Case Hardening

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Carburizing Introduction

By. R. B. Schenck*

The process now known as carburizing dates back many centuries. The old cementation process in which a material similar to our puddled iron was made to absorb carbon from charcoal without fusion was the sole source of steel at one time. By a sufficiently prolonged exposure small bars of hammered iron were carburized more or less throughout their full cross section resulting in the so-called "blister steel" of that day. Later came the melting of blister steel in crucibles to be followed finally by our modern methods of melting and refining.

As practiced today, the process of carburizing is applied to finished or semi-finished articles of ferrous metal with the object of increasing the carbon content of the surface so that when subjected to suitable heat treatment the surface portions so carburized will be substantially harder than the underlying metal. Thus, a low carbon steel article which in its original condition will harden but little on quenching, can be carburized and then quenched, producing a hard, wear resisting surface and a softer interior. The combined process of carburizing followed by hardening has been long known as "case hardening."

This combination of hard surface and softer interior made possible by case hardening is of inestimable value in modern engineering practice. By the use of alloy steels, great strength and toughness in the core can be combined with extreme surface hardness, resulting in a composite structure capable of withstanding certain kinds of stress to a high degree. For less exacting requirements, there are innumerable applications where low or moderate core properties together with a high degree of surface hardness can be readily obtained with cheaply fabricated, low priced carbon steels.

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Prepared for the Subcommittee on Carburizing. The membership of the subcommittee was as follows: R. B. Schenck, chairman; E. F. Davis, J. A. Dow, R. W. Schlumpf, H. W. McQuaid, and G. T. Williams.

Carburizing Methods

By R. B. Schenck*

General—Commercial carburizing may be accomplished by any one of the following methods: (1) pack carburizing; (2) gas carburizing; or (3) liquid carburizing.

As implied by the above terminology, the three methods depend respectively upon the action of agents which are solid, gaseous or liquid at the carburizing temperature.

In pack carburizing the work is heated in contact with a solid carburizing compound in a closed container. In the gas method the work is exposed to the action of a carburizing gas in a heated chamber. In liquid carburizing the work is immersed in a fused carburizing salt.

A choice of the method to be used depends upon so many factors that it becomes rather difficult to set up any definite rules to be followed. The design of the part, type and depth of case, permissible distortion, production volume, initial investment and operating cost, must all be taken into consideration and present such an involved picture that the only correct procedure is to judge each individual case on its own merits.

Pack Carburizing—The pack method is the oldest and for years has been the one most extensively employed. In its various modifications it has been used for practically every kind of an article that could be carburized, ranging from type-writer parts to armor plate. It is usually considered the most fool-proof of the three methods, and the safest to use in the absence of trained supervision.

The usual form of the pack method, frequently referred to as "box carburizing," lends itself readily to either batch or continuous furnace operation. The packing material provides an excellent support for pieces which tend to warp in heating and the natural slow cooling in the containers, where direct quenching is not used, tends to hold warpage to a minimum. The outstanding disadvantages are the time consumed in heating the charge, the high labor cost involved in packing and unpacking and the preclusion of automatic quenching.

The only other form of pack carburizing which deserves mention here is the "rotary retort" method, suitable only for batch operation. This modification of the pack method has been in use for many years. Its application is limited to parts which can withstand the necessary tumbling action without injury. The labor cost is low since the work is handled in bulk for both charging and discharging. The charge may be either direct quenched or slowly cooled in a suitable container. Heating is extremely rapid thus materially reducing the time required for a given depth of case. For parts which can withstand the rough handling of this method, it is probably the most economical one yet developed.

Gas Carburizing—Although the gas method of carburizing is not by any means a new one, it has never been used as extensively as its possibilities seem to warrant. However, gas carburizing is now undergoing intensive development and according to present indications may eventually replace other methods to a very large extent.

One of the oldest commercial forms of gas carburizing is the rotary retort method, very similar to the one described under Pack Carburizing but using gas instead of solid material. In general, the same advantages and limitations apply to both. Stationary horizontal and vertical retorts, also limited to batch operation, are used to some extent.

The most noteworthy development has been in equipment for continuous gas carburizing with either automatic quenching, hand quenching, or slow cooling. Labor costs are low, but initial investment is high and large units operated at high output are necessary if full operating economy is to be attained. The controls are rather complicated and the successful operation of these units requires trained supervision.

For work which can be handled in sufficient quantity by the above method, the operating costs can be reduced to a low figure, especially where automatic quenching is employed. Temperature and case depth are extremely flexible. Units

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are now in operation at 1500°F. producing cases of 0.005 in. on automotive transmission gears. Equally satisfactory operation is being obtained with heavy cased work at temperatures as high as 1800°F.

An important characteristic of gas carburizing is the ease with which the case composition can be controlled. By suitable adjustment of time, temperature and gas composition, the surface carbon and the carbon gradient can be varied to meet almost any requirement. Additional flexibility is available in batch operation by varying the rate of flow and composition of the gas throughout the cycle.

Liquid Carburizing—Progress in the technique of liquid carburizing, both with respect to the carburizing agent and the equipment, has been extremely rapid in the last few years. The new activated baths with their higher rate of penetration and better quality of case, together with improved methods of heating and control, are extensively replacing the old cyanide pot in the more progressive plants. Automatic handling is also being introduced in certain applications with marked success.

Liquid carburizing is used for light cases at moderate temperatures. For case depths of more than about 0.030 in. other methods are employed. The process is extremely flexible, easily controlled and particularly well adapted to small units. With continuous operation and automatic quenching, labor costs can be reduced to a low figure. The largest single item of operating expense is the carburizing salt.

The Mechanism of Carburization

By R. W. Schlumpf*

Sources of Carbon—The carburization of steel is effected by heating it to relatively high temperatures (usually within the range of 1600-1800°F.) in contact with carbon-bearing materials which are capable of yielding carbon to the metal surface. These carburizing materials can be gases, liquids or solids.

The most important carburizing gases are carbon monoxide and hydrocarbons such as methane, ethane, propane and butane, which exist as gases at atmospheric temperature and pressure.

Carbon monoxide is the carburizing agent in the so-called "pack" method of carburizing, where the metal to be carburized is packed in a sealed container with some form of free carbon to which is usually added a metallic carbonate. The metallic carbonate or "energizer" decomposes when heated and yields carbon dioxide gas which in turn reacts with the free carbon in the mixture to form carbon monoxide gas.

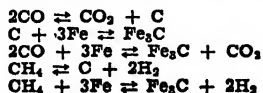
The hydrocarbons, methane and ethane, are the principal carburizing agents in the so-called "gas" method of carburizing where either natural or manufactured gas containing relatively high percentages of either or both of these hydrocarbons is brought in contact with the steel at carburizing temperatures. Propane and butane are liquified under pressure for transportation and storage, being converted to the gaseous state preceding their introduction to the high temperature of the carburizing chamber. Hydrocarbons that exist as liquids at atmospheric temperature and pressure are converted to gases when introduced into the high temperature carburizing chamber.

Carburizing liquids are generally defined as chemical salts of the cyanogen radical type that yield carbon by direct or indirect action when heated in contact with the steel. The temperature required for carburizing action is above the melting points of these commercial salt-type carburizing materials, hence these carburizers are used in the liquid state and the process is referred to as liquid carburizing.

Solids have no practical importance as direct carburizers. The solids involved in the important commercial carburizing processes all have an indirect action in that they are only accessory to the generation of the direct-acting carburizing agent. It is generally agreed that steel cannot be carburized in direct contact alone with any of the commonly used forms of free carbon. It has been demonstrated that steels such as S.A.E. 1020 and 3115 show no measurable amount of carburization after heating to a temperature of 1700°F. for several hours in contact with hard-wood charcoal in an atmosphere evacuated to about 5 mm. of mercury. In repeating this test with the vacuum pump disconnected and the container closed with a non-pressure-tight seal a case depth of about 0.060 in. was obtained under the same conditions of time, temperature and carburizing material.

Molecular carbon such as soot that has been formed by the dissociation or decomposition of a carburizing gas is relatively inactive and can become active for carburizing only by recombining with another element to form a carbon compound.

Absorption and Diffusion of Carbon in Steel—All carburizing depends on the ability of the carburizing medium to supply atomic carbon to the metal surface. Whether this atomic carbon passes directly into the space lattice until a saturation value for the existing temperature is reached or whether the carbon atom is conveyed into the metal by a chain of interactions in which iron carbide is first formed at the surface and then, through dissociation, yields carbon to the next group of iron atoms is still controversial. The equations representing the carburizing reactions for two of the common gaseous media may be stated as follows:



The equilibria involving these reactions in the carburization of steel are shown in the diagrams prepared by various investigators.¹⁻¹¹

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Iron carbide can be formed by the reaction of iron with carbon monoxide at temperatures as low as 1150°F. This would indicate that the formation of carbide at the surface of the metal is the first step in the mechanism by which carbon is absorbed. This belief is supported by the fact that at low carburizing temperatures, where the rate of diffusion is low, it is possible to build up a surface carbon content by the continued formation of iron carbide considerably in excess of the saturation value for the austenitic solid solution. When carburizing at 1700°F. it is likely that carbon atoms first saturate the austenitic solid solution with carbon and when supersaturated the austenite precipitates Fe_3C . When carburizing at the low temperature of 1150°F. the ferrite supersaturates in the same way and precipitates Fe_3C .

Diffusion tests at higher temperatures, with the gaseous carburizing medium removed, show that carbon will diffuse inward from this surface carbide. The ability of iron carbide to furnish diffusible carbon is demonstrated by tests where white iron particles were placed in a low carbon steel chamber which was then evacuated to about 5 mm. of mercury, heated to 1700°F., held for several hours and then slowly cooled. After cooling to atmospheric temperature the vacuum pump was disconnected, the steel chamber sectioned and found to be carburized where it had been in contact with the white iron particles. The bottom part of the chamber, in contact with the white iron particles of about 100 mesh size, was carburized to about twice the depth that was observed immediately above where 20-40 mesh particles were placed on top of the 100 mesh layer. The general appearance of the contour of the inner edge of the case indicated that the carburization had taken place by linear diffusion of carbon from each point of contact of a white iron particle. The top part of the chamber above the charge of the iron carbide-bearing particles showed no carburization. This test was repeated with pulverized hardwood charcoal under the same conditions of temperature and pressure and no carburization was observed.

The degree to which the carburizing gas actually penetrates beneath the surface of the steel before liberating atomic carbon or reacting with the steel to form iron carbide is controversial. While there is definite evidence that oxygen as well as carbon is released for diffusion into the steel when carburizing with carbon monoxide and that hydrogen can diffuse along with the carbon when carburizing with methane, the exact extent to which these carbon-bearing gases might penetrate before decomposing has not been definitely determined. It can only be broadly stated that the extent of penetration would be determined by sub-surface equilibria in the system $\text{CH}_4\text{-C-H}_2\text{-Fe}_3\text{C}$ -austenitic solid solution when carburizing with methane or $\text{CO-C-CO}_2\text{-Fe}_3\text{C}$ -austenitic solid solution when carburizing with carbon monoxide. It has been suggested that the jog usually observed near the surface in carbon gradient curves for the lower carburizing temperatures might indicate the zone of gas penetration and that portion of the curve above the jog represents gas decomposition, carbide formation and carbon diffusion while the curve below the jog represents carbon diffusion only.

Another factor that might play an important part in the mechanism of carbon absorption is the possible metal vapor phase in existence at the surface of the steel. Evidences of this metallic vapor phase or sublimation of the iron have been observed in carburizing with hydrocarbon gases but have not been studied in sufficient detail to identify or definitely establish the authenticity of this factor. Samples of soot from a basket taken from a production methane-carburizing heat were

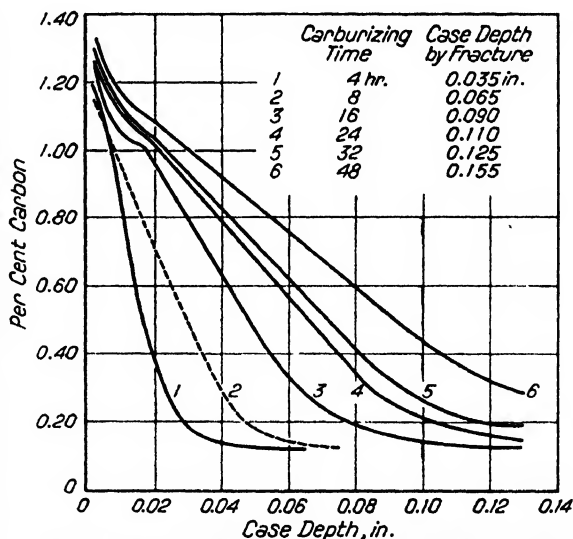


Fig. 1—Carbon Gradient Curves for S.A.E. Steel 3115. Carburized at 1700°F. in Hardwood Charcoal, Coke, Sodium Carbonate Compound.

found to analyze as high as 30% iron. The iron was apparently thoroughly distributed throughout the soot and was not confined to layers immediately in contact with the surface of the steel that had been carburized. Evidences of a metallic vapor phase have been found in heating other metals in the presence of hydrogen in a sealed container to temperatures well below the melting point. While it is possible that this metallic vapor phase might be a volatile metallic compound rather than the true vapor phase of the metal we cannot neglect to consider that it would be expected to be a very active intermediate agent in the transference of carbon from the carburizing medium to the steel.

Catalysis is still another factor that is evident in carburization but not thoroughly understood. It has been proposed that the metallic oxide resulting from the decomposition of a metallic carbonate energizer in the commercial pack carburizing compound acts as a catalyst in the $\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$ reaction.¹³ This is supported by the observation that the oxide when used alone as an energizer is effective. There are evidences that the surface of the steel being carburized and the walls of the container have a catalytic effect on the reactions involved in carburizing. It has been noted that under the same conditions of temperature, gas flow and pressure in a carburizing process with methane that different types of metals used for the container or fixtures for holding the work will exert different influences toward the deposition of free carbon. The probable catalytic effect of an iron oxide skin produced on the surface of the steel by the introduction of a closely controlled amount of water vapor previous to the introduction of the carburizing gas in a retort type gas carburizing operation has been reported and discussed.¹⁴ The exact mechanism of catalysis in carburizing is still elusive and demands further study.

Under some conditions oxygen-bearing gases present in pack carburizing appear to influence the size of the austenite grains developed in the case and the microstructure of the slowly cooled product (McQuaid Test, page 750).

Mechanism of Cyanide Hardening—The reactions occurring in the cyanide bath are somewhat complicated and more or less hypothetical. Tests made in vacuo indicate that the absence of oxygen prevents carburization. It is therefore generally recognized that the conversion of sodium cyanide to sodium cyanate is an essential step in the process of cyanide hardening.

The accepted chemistry of the process is as indicated:

1. $\text{NaCN} + \text{O} = \text{NaCNO}$
2. $4\text{NaCNO} + \text{heat} = 2\text{NaCN} + \text{Na}_2\text{CO}_3 + \text{CO} + 2\text{N}$
3. $2\text{CO} = \text{CO}_2 + \text{C}$

Sodium carbonate is the ultimate decomposition product of sodium cyanide when operated commercially in a fused bath.

The various activated baths differ in composition. Barium chloride or carbonate are ingredients in several baths. Calcium cyanamid with a calcium and sodium

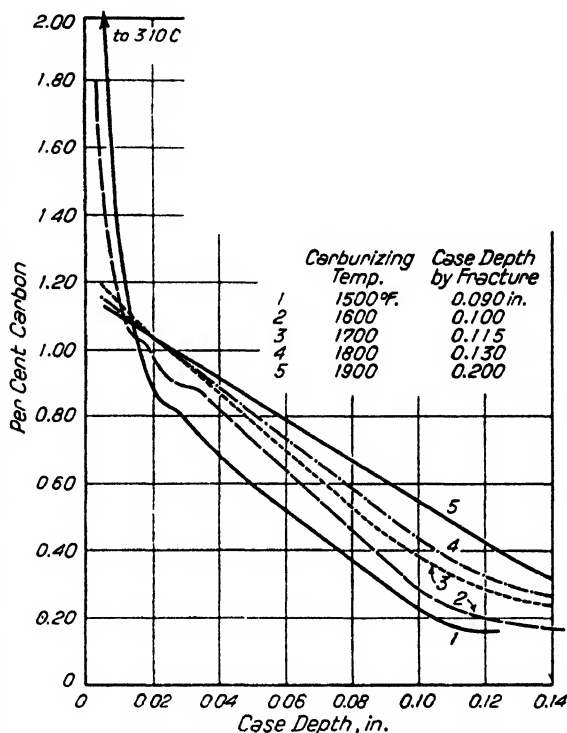


Fig. 2—Carbon Gradient Curves for S.A.E. Steel 3115. Carburized at different temperatures in same type compound as Fig. 1.

chloride is another type. The chemical reactions are, however, all based upon the employment of the cyanogen radical introduced by a cyanide compound.

The chemistry of a typical activated bath utilizing barium salts may be illustrated as follows:

1. $\text{Ba}(\text{CN})_2 = \text{BaCN}_2 + \text{C}$
2. $\text{BaCN}_2 + \text{Na}_2\text{CO}_3 = \text{BaO} + 2\text{NaCNO}$
3. $4\text{NaCNO} + \text{heat} = 2\text{NaCN} + \text{Na}_2\text{CO}_3 + \text{CO} + 2\text{N}$
4. $2\text{CO} = \text{CO}_2 + \text{C}$

Those containing calcium, where CaO would be formed in the second reaction, produce infusible residues in the bath.

Factors Affecting the Distribution of Carbon in the Case—Regardless of the exact manner in which the carbon becomes a part of the metal, carbon gradient analyses indicate that it diffuses in accordance with the laws of linear diffusion generally definable by a diffusion equation such as Carslaw's equation for linear heat flow.

In the carburizing process the rate of diffusion depends on temperature, carbon concentration gradient, pressure and factor of diffusivity for the particular steel in use. Diffusion rate increases quite rapidly as the temperature increases. The effect of carbon gradient is manifest in the speed with which a low carbon steel can be carburized as compared with a high carbon steel. Pressure is thought to be a factor only in so far as it influences the concentration of active carburizing gas in the surface gas-metal equilibria. The diffusivity factor of the steel is related to its chemistry in so far as the elements other than iron and carbon are concerned. It has been generally observed that those alloy elements which are not essentially carbide formers tend to retard the progress of carburization by impeding both the surface carbon build-up and the diffusing action. The elements that are strong carbide formers tend to increase the surface carbon concentration and the speed of carburization.

At temperatures within the usual carburizing range where the steel exists as austenitic or gamma iron solid solution there is the tendency, with high concentration of carburizing agent, for the carbon concentration at the surface of the steel to increase until the saturation value for the austenite (as indicated for any given temperature on the SE line on the iron-carbon diagram) is attained and then continue increasing by the formation of free iron carbide or cementite. The degree to which the carbon can be built up in solution in the austenite or to continue building up by the formation of cementite after the austenite is saturated is indicated in equilibrium diagrams prepared by various investigators, as previously mentioned. While the carbon concentration is building up at the surface the inward diffusion of carbon is in progress. The resulting degree of carbon concentration in successively deeper parts of the case (from the surface to the core) after carburizing at a given temperature therefore depends on the ability of the diffusing action to overcome the tendency to build up the

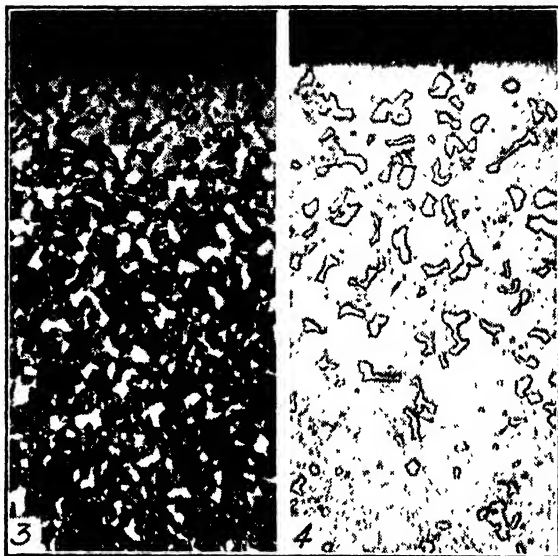


Fig. 3

Fig. 4

Fig. 3—Surface of S.A.E. Steel 3115 after carburizing 150 hours at 1500°F. in the same type compound as Fig. 1 and slowly cooled from the carburizing temperature. Shows concentration of iron carbide. Depth of 0.002 in. analyzed 3.10% carbon. Etched in nital $\times 250$.

Fig. 4—Same steel and compound as Fig. 3. Carburized 130 hours at 1500°F. and quenched in water from carburizing container. Shows existence of free carbide or cementite at the carburizing temperature. Etched in Picric acid $\times 250$.

carbon at the surface. At the common carburizing temperature of 1700°F. a set of curves showing carbon concentration in S.A.E. 3115 steel in a conventional hardwood charcoal-coke mixture energized with sodium carbonate is given in Fig. 1. It will be noted on these curves that the steep gradients established in the shorter periods of carburization indicate the tendency for rapid build-up of carbon at the surface. With the longer periods of carburization the surface carbon increases only slightly over that observed for the shorter periods of carburization, being continuously depleted by diffusion. At this temperature the balance between carbon build-up and diffusion results in a surface carbon concentration closely approximating the equilibrium value for saturated austenite as indicated on the SE line of the iron-carbon diagram.

If the carburizing temperature is lowered sufficiently the diffusing speed is reduced to the extent that the carbon can build up to values far in excess of the equilibrium value for saturated austenite. This condition is shown in the set of curves (Fig. 2) representing carburization of S.A.E. 3115 steel at different temperatures to approximately the same case depth in the same type of compound as above. The carburizing was sufficiently vigorous throughout the period of carburization to facilitate the saturation of the austenite and then continue the formation of iron carbide. At the lowest temperature on this set of curves (1500°F.) the core still contains alpha iron which further retards diffusion of the carbon. The surface carbon build-up at this low temperature is illustrated in the photomicrographs of Fig. 3 and 4.

While the selection of carburizing temperature for certain jobs, in some instances, might be based on the desire to produce a predetermined carbon gradient in the case, the temperature in the majority of commercial applications has been arrived at through counterbalancing the diffusion rate factor against the effect of the higher temperatures on the physical properties of the steel and on the carburizing equipment.

The relation of time to carbon penetration or case depth is illustrated in the set of curves of Fig. 5 prepared from test runs in a production vertical stationary type gas retort using natural gas at atmospheric pressure. These curves approximate closely the rates obtainable regardless of the medium used.

In the pack carburizing process the carbon gradient in the case can be controlled to a certain extent by the choice of the form of carbon to be used in the compound. If the factors in a pack carburizing operation are fixed as regards compound, temperature, and chemistry of the steel the carbon gradient of the case can be controlled by a diffusing cycle, usually requiring a second or additional operation.

In the gas carburizing process the factor of surface gas-metal equilibria can be more easily manipulated by varying the gas flow rate, introduction of diluents, interruption of gas flow, and variation of chamber pressure, than by varying the temperature, due to the effect of the latter on gaseous equilibria. In the $\text{CH}_4 \rightleftharpoons \text{C} + 2\text{H}_2$ system the active carburizer (CH_4) becomes less stable as the temperature increases while in the $2\text{CO} \rightleftharpoons \text{C} + \text{CO}_2$ system the active carburizer (CO) becomes more stable with increasing temperatures.

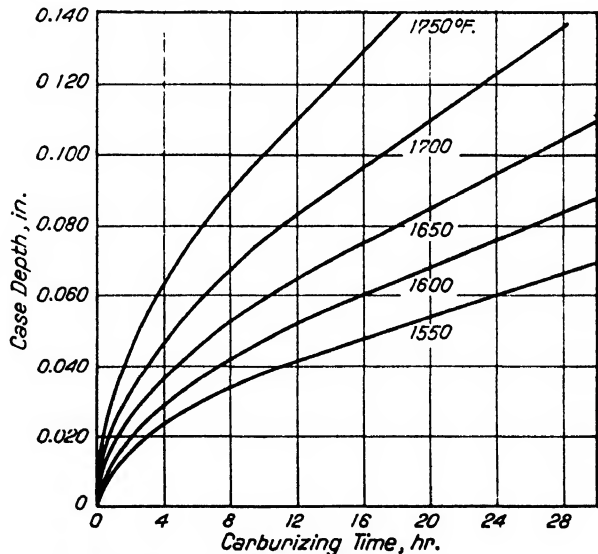


Fig. 5—Relation of Time and Temperature to Carbon Penetration. Carburized in vertical gas retort using natural gas (95-98% methane). Measurements made on triangular test specimen. S.A.E. steel 3115.

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Selection of Carburizing Steel, Case Depth, and Heat Treatment

By Gordon T. Williams*

Introduction—A great variety of steel types may be used for the production of case hardened parts having the qualities described later, that is, a hard, wear or fatigue resistant surface on a core of relatively tough, shock-resistant nature, resulting in a part of required durability.

The following two basic factors must be considered first when selecting a steel for use in this process: a. Quenching medium to be used as demanded by sections and distortion limits; b. Type and degree of stresses to which the finished part will be subjected.

Since these are also the factors which will determine the heat treatment to be used, obviously steel and treatment must be simultaneously considered.

The quenching medium to be used is ordinarily rather easily decided. Water or aqueous solutions will be preferred, due to low cost of medium, rapidity of cooling, and ease of subsequent cleaning; such coolants will be used wherever simple shapes or massive sections permit their application. When sections are thin so that cracking or warping is probable, and when accurate contours must be preserved, as in gears, slower media, usually oil, must be used. From such consideration decision can be made as to relative hardenability required and permitted in the steel.

The quenching medium must be selected with regard to attainment of desired hardness of the carburized surface and also in many cases the attainment of required hardness and strength of the core at some depth below the surface. The critical cooling velocity is, of course, the factor here. If maximum surface hardness is the only requirement, steel containing only carbon or low amounts of alloying elements will be selected, to be quenched in water. If, however, too much distortion would result from this quench, or cracking is encountered, then oil will be used, and a steel must be selected having sufficient alloying elements that the lower cooling velocity will still be above the critical rate for the steel.

The type and degree of stresses to which the finished part will be subjected will indicate the physical properties demanded in the core, as well as the preferred metallographic character of the case and its depth. Static compressive loads normal to the surface require only sufficient depth of case and hardness of core that the former does not deform when stressed. A case too shallow or a core too weak will result in surface deformation under the load. This type of failure is often called "brinelling" because of its similarity to the effect of Brinell testing of a hardened case. Abrasion of the case hardened surface will usually be best resisted by a case of maximum hardness, with low contents of austenite to resist flowing under the load, and sufficient depth to give reasonable life in wear. However, wear is of several types, and there are many exceptions to the above statement; type of case must be selected to best resist the specific kind of abrasion encountered.

When bending stresses are encountered, the factors of core hardness and case depth are so directly related that they must be simultaneously considered, as shown by Woodvine. Fig. 1 illustrates the Woodvine' principle. In this diagram, stress in a beam is plotted against distance from the neutral axis, the points along the line OA. The endurance limit of the case is represented by BC, that of the core by DG. The line BPQG thus represents the endurance limit of the case hardened piece. Were the core fatigue limit lower, the point Q would be to the left of the stress line OA, and fatigue failure would occur in the core just below the case. The strength of the over-all part may thus be increased by increasing the core strength (hardness) or by increasing the case depth. Internal stresses may weaken the case but do not add to the strength of the core, so the core is of more importance than theoretical considerations would indicate. Probably due to internal stresses, increase in case depth does not raise the case strength except with certain treatments, as shown by McMullan.²

The combination of case depth and core strength must be sufficient that the stress does not exceed the endurance limit of the material at any given distance from the neutral axis. It must be noted that stress-raisers, such as notches and tool

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marks, will make the direct application of this principle ineffective.³ Since the rate of carburization falls off rapidly as greater depths are sought, a more economical method of meeting the stress-resisting requirements is by improving the properties of the core. Also, increased case depth is attended by greater internal stresses after hardening and greater tendency to spalling of the case.

For resistance to such service the steel to be case hardened should be selected on the basis of physical properties attainable in the core after a heat treatment.

The required core strength may be insured by the use of steels of sufficient carbon or alloys or both to give hardening (strengthening) to the desired degree.⁴ Carbon alone will not cause the development of high core properties except with high quenching rates, as in thin sections or with drastic cooling. Thus when accurate contours are to be preserved and a slower (oil) quench must be used, the core hardening qualities of carbon must be supplemented by alloying elements; the amount of these two effects being determined by the sections and strength requirements.⁵ Since the percentage of alloying elements is reflected in the cost of the steel, and since the higher alloy steels in general are more difficult to process both in machining and in heat treating operations, there is a growing tendency toward the use of moderately alloyed steels with carbon percentages higher than previously employed. Until a few years ago, "carburizing steels" had 0.08-0.25 carbon, the lower ranges being preferred. Today, however, gears and other automotive parts, for example, are being made to withstand higher stresses by the use of moderately alloyed steels with carbon contents up to 0.40%, and often the case depths are being decreased, as permissible in accordance with Fig. 1.

Selection of Steel

Plain Carbon Steels—In this class are those steels containing only carbon (in addition to the usual percentages of such elements as silicon and manganese), or such slight amounts of alloying elements that the critical cooling velocity of the carburized case is normally only reached by quenching in aqueous media. Chromium up to 0.30%, or manganese up to 1.5%, are sometimes deliberately added to the plain carbon steels to accentuate the hardness or wear resistance of the surface, but these quantities may not be sufficient to permit full hardening in normal sections with oil or similar media. Carbon above 0.25% is infrequently used in standard practice due to brittleness of such steels in the fully quenched core. Core strengths of about 100,000 psi. with adequate toughness can rarely be exceeded with these steels. Heat treatment is simple and easily controlled.

Moderately Alloyed Steels—Those steels containing from 1-2% total alloying elements such as nickel, chromium, manganese, vanadium, and molybdenum, in addition to carbon, have sufficient hardenability that maximum hardness is usually attained by oil quenching, and desired core properties up to a tensile strength of 175,000-190,000 psi. are obtainable with suitable toughness by selection of analysis. In this class also fall the steels containing 0.20 to 0.30% molybdenum with no other alloys, made with controlled hardenability. Carbon content up to 0.40% may be specified to increase the core strength, the alloys providing the required toughness and depth-hardening characteristics. The differences between the various alloy types in this classification are difficult to demonstrate, being easily overshadowed by differences in processing technique and individual preferences.⁶ In general, there is a growing tendency toward the use of chromium as the principal alloying element due to decreased likelihood of austenite retention. The ready response of steels of this general class to heat treatment has permitted simple and accurate heat treating procedures to be established.

High Alloy Carburizing Steels—In some instances the sections and service requirements are such that a total of alloying elements over 2% must be used to give the desired core properties. The elements used are the same as above, but carbon content is held to 0.20 maximum because of the intense hardening power of these steels. Low quenching rate is required to harden to the maximum. Extreme core toughness and strength may be developed. The cost of steel and processing limits the use of these steels. Probability of austenite retention in the hardened case necessitates special, sometimes elaborate, heat treating cycles.

Grain Size and Abnormality—The grain growth tendency of a specific piece of steel at the carburizing temperature has a marked effect on physical properties and distortion after subsequent hardening. Steels of McQuaid-Ehn grain size of 5 or finer are almost invariably preferred and usually demanded. In a limited number of applications, the greater hardenability of the coarser grained steels warrants their

use in spite of increased distortion and reduced toughness.¹ Abnormality often accompanies fine grain in the McQuaid-Ehn test. Although the cooling velocity for full hardening must be greater for an abnormal than a normal steel of a given analysis, the change in critical rate is marked only in plain carbon steels when NaCl or NaOH solution is often required in quenching these to avoid soft spots. "Normal" steel is therefore frequently specified in the plain carbon types where freedom from soft spots after water quenching is required. Specifications as to normality are, however, rarely used in the alloy types. Abnormality, implying rapid spheroidization of carbides, may be definitely advantageous in avoiding residual networks of carbide after certain treatments.

Selection of Case Type and Depth

Case Depth—For ordinary engineering application several combinations of case depth and steel analysis may be used. In accordance with the Woodvine diagram, Fig. 1, an increase in core strength, accomplished by increasing alloy content or carbon content or both, permits a reduction in the depth of case required to resist bending stresses. Likewise, if compressive loading is to be resisted, an increase in core hardness will aid in giving a nondeflecting case, as will increased case depth. For resistance to abrasion only, service life will usually be proportional to case depth alone. Obviously, therefore, a wide range of case depths may be employed on any given part, consideration of over-all properties and manufacturing economy determining the steel analysis and selected depth.

As shown by time-penetration curves in the article on Mechanism of Carburizing, case depth increases rapidly with short times at heat, but after approximately 8 hr. the rate of penetration reaches a low and constant value. Consequently, case depth specifications are kept low enough that time required is not excessive. Carburizing costs include not only labor, which is little affected by increased time in furnace, but also furnace and heat resisting alloy costs.

The most common case depth is probably 0.045-0.060 in. Such a depth is obtained in 8 hr. at 1700°F.

Decrease in depth may be permitted when service is light or when core properties are improved by use of higher carbon or alloy content. As discussed later, this principle is being increasingly applied to gears, giving a product economical as regards steel and processing cost, as well as meeting the requirements indicated by the Woodvine diagram. Small or thin parts may of necessity be made with shallow case because of the brittleness which would otherwise result. A frequently applied rule-of-thumb states that the thickness of the case must not exceed one-sixth the section, if toughness is to be had.

Increased case beyond the normal depth is expensive to attain, and should only be specified when demanded by service requirements. Heavy duty gears, for example, are often made with case depth of 0.060-0.090 in. and parts requiring long life under highly abrasive conditions may have cases as much as $\frac{1}{4}$ in. deep. If much of the case is to be removed by grinding, obviously this must be allowed for in carburizing.

In connection with selection of case depth, it is well to bear in mind that, as shown in the article on Mechanism of Carburizing, the maximum carbon content and thus the maximum actual hardness at the surface are relatively independent of case depth. However, if the hardness test to be applied involves a heavy load with considerable penetration of the piece, a relatively deep case may be necessary to give a satisfactory hardness test result. For example, a high Rockwell C reading can be obtained only with cases having a hard layer over 0.025 in. deep, yet a case but 0.005 in. deep will give as great file hardness as the deeper cases. The readings obtained also depend on the support given the case by the core. Allowance should be made for these factors in selecting test methods for use with lighter cases.

Table I, from Boegehold and Tobin, summarizes typical applications and requirements.²

Type of Case—For two reasons it may be desirable to avoid a hypereutectoid layer. First, if the work is slowly cooled from carburizing, proeutectoid cementite will be rejected to the grain boundaries, usually forming a network. This will be redissolved in the hardening treatment but slowly, especially if the carbides are complex, and only if heated to the required A_{cm} temperature. Residual grain-boundary cementite in the finished piece is a frequent cause for failure due to brittleness. Second, even though direct quenching is employed and the separation of proeutectoid cementite inhibited, the hypereutectoid carbon content will tend

Table I
Typical Automotive Carburizing Applications and Requirements*

Case Depth	Typical Parts Made from Low Carbon Steel	Surface Condition When Treated	Requirements	Typical Parts Made from Medium Carbon Steel	Requirements
Up to 0.020"	Push Rod Balls Push Rod Sockets Speedometer Gears Shackle Bolts Shifter Forks The Rod Ball Studs The Rod Ball Stud Sockets Water Pump Shafts	Finished before treatment except for possible polishing operation. When nitrided 0.0003" to 0.001" per side removed for maximum wear resistance. Finished before treatment except for possible polishing operation. Generally semi-finished before treatment and finish ground after treatment.	High degree of wear resistance. Clean surface after treatment. High degree of wear resistance. Sufficient strength to withstand service loads. Enough case to permit finish grinding and maintain high hardness for necessary wear resistance.	Transmission Gears. Transmission Main Shafts and Synchronizer Sleeves. (Surface generally finished before treatment.)	Maintain or increase surface carbon for higher degree of wear resistance and greater fatigue resistance to high occasional or shock loading. Clean surface after treatment.
0.020" to 0.40"	Pitman Arm Ball Studs Intermediate Steering Arm Ball Studs Steering Arm Bushings Valve Rocker Arms Shafts Gear Shifter Shafts Brake and Clutch Pedal Shafts Water Pump Shafts	Finished before treatment except for lapping operation.	High wear resistance to resist sliding, rolling or friction of abrasive nature. Resistance to heavy crushing. Resistance to high alternate bending stresses.	Transmission Gears. Ring Gears. Drive Pinions. (Surface finished before treatment except for lapping operation)	Increase carbon content at surface for greater wear resistance, load carrying ability and fatigue resistance. Clean surface after treatment.
0.040" to 0.060"	Ring Gears Drive Pinions Transmission Gears Side Gears Side Pinions Piston Pins Steering Knuckle Pins Side Pinion Axes Reverse Idler Gear Shafts Counter Gear Shafts	Finished before treatment except for lapping operation. Semi-finished before treatment. Finish ground after treatment.	High wear resistance to resist sliding, rolling or friction of abrasive nature. Resistance to heavy crushing. Resistance to high alternate bending stresses. Operate frequently in bronze bushings. High wear resistance. Resistance to relatively high unit loads that cause Brinelling. Resistance to fairly high alternate bending stresses. King pins also require resistance to high instantaneous or shock loads.		
Over 0.060"	Roller Bearings **Camshafts	Semi-finished before treatment	Resistance to heavy rolling action. High wear resistance. Resistance to shock. Resistance to relatively high unit loads with a rapid sliding action.		

As service becomes more severe as in trucks and buses, the depth of case for corresponding parts may be somewhat deeper and the general tendency is to change to a steel which permits better physical properties, especially in the core.
 *More case than actually necessary to satisfy service requirements put on parts of such length as these in order to avoid necessity of straightening to extremely accurate degree before grinding.
 **Carburize deeper than necessary to satisfy service requirements to compensate for inaccuracies of machining due to length of these parts, distortion due to heat treatment and insure sufficient case after grinding for necessary hardness and wear resistance.

to increase austenite retention. For most applications a martensitic case free from austenite is preferable, consequently, if the steel is highly alloyed and thus susceptible to austenite retention, carbon content of the case should be held to the lowest amount compatible with full hardness, usually eutectoid content.

In certain applications, presence of cementite in the case is desirable to aid in wear resistance. For such applications it is important that the carbon content be high, the excess carbides being preferably in spheroidal form.

Heat Treatment Classification—A carburized piece must be regarded as a duplex material, that is, a high carbon surface, and a low carbon core, with a more or less gradual transition from one to the other. Two critical temperatures are thus involved in hardening, and the excess carbide of the case may or may not be dissolved at the hardening temperature selected.

Table II
Heat Treatment Classifications

S.A.E. Steels*	Alloys	Critical Points Case A_{c1} Core† A_{c3}	Preferred Treatments See Fig. 2	Quenching Medium	Tendency to Retain Austenite
1015	None	1360°F. 1605°F.	A,D	Water or 5% NaOH Solution	Slight
1315	Mn 1½%	1345	A,D	"	"
2315	Ni 3½%	1300	C,D,F	Oil	Moderate
2515	Ni 5%	1250	D,F	"	Strong
3115	Ni 1¼, Cr ½%	1355	E,C	"	Slight
3215	Ni 1¼, Cr 1%	1350	D,F	"	Moderate
3312	Ni 3¼, Cr 1½%	1330	D,F	Oil or Alr Oil	Strong**
3415	Ni 3, Cr ¾%	1330	D,F	"	"
4115	Cr 1, Mo ¼%	1395	E,C	"	Strong**
4615	Ni 1¼, Mo ¾%	1335	E,C	"	Slight
4815	Ni 3¼, Mo ¾%	1300	E,F	"	Moderate
5115	Cr 1%	1410	E,C	"	Slight
6115	Cr 1, V 0.15%	1420	E,C	"	Slight
Ni-Cr-Mo	Ni 1½, Cr ½, Mo ¼%	1350	E,C	"	Moderate

*All steels preferably of grain size 5 or finer.

† A_{c3} of core will decrease as carbon is increased.

**Spheroidization of excess carbide by subcritical treatment may be used to decrease austenite retention.

Fig. 2 illustrates the requirements and summarizes the usual methods by which carburized work is heat treated,⁸ and Table II shows critical temperatures and preferred treatments for usual carburizing steels.

Annealing—If subsequent distortion is to be minimized, the annealing temperature should be at least 50° above any temperature to be used later (carburizing). This will insure absence of pent-up stresses which might later cause distortion. Rate of cooling from the annealing temperature must be regulated to give uniformity from piece to piece, and to provide the required structure for best machinability. The carburizing operation and the later hardening are severe treatments, so maximum freedom from internal stresses must be provided by careful annealing practice on any but the simplest shaped parts.

Carburizing—Type of case and its depth must be carefully controlled.^{1,9} The temperature employed will usually be 1650-1700°F. to give a fair rate of penetration without unduly increasing furnace costs. Uniform temperatures must be provided to produce uniform carburizing, hardening response, and to control distortion.

Cooling from Carburizing—Since carburizing is conducted above the critical temperature of case and core, hardening of both will obviously occur if the work is cooled from this operation faster than the critical cooling rate.¹⁰ Prior to the advent of steels controlled to maintain a fine grain size at carburizing temperatures, such "direct quenching" was useful only for parts of regular shape and section because of the danger of cracking and distortion. Currently, however, an increasing portion of carburized work is being direct quenched into a suitable coolant, and in most cases if a fine grain steel is used, distortion is found to be lower and more regular than if parts are slowly cooled and then reheated for hardening. The greater difficulty of handling work from the higher temperature (carburizing) and in the quantities which are delivered discontinuously from carburizing furnaces, as opposed to reheating for hardening, have led some to prefer the latter procedure. A further handicap to the full use of direct quenching is the greater tendency toward reten-

tion of austenite in the hardened case, due to the higher temperature and increased cooling velocity." The higher alloy steels can rarely be used in the direct quenched condition for this reason, and many of the moderate alloy steels retain sufficient austenite so that the treatment is not acceptable, especially when parts will be subject to rolling under load (such as spiral or hypoid gears). Retention of austenite and distortion may be decreased in direct quenching by retarded cooling to a temperature above the A_r before quenching. This may be accomplished by transferring the work to a furnace held just above A_r , and stabilizing the work temperature at this level before quenching; a cyanide bath may be used, thus simultaneously accentuating surface hardness. Quenching from the carburizing temperature may be followed by reheating above the A_c of the case to give maximum refinement thereof, with minimum austenite retention. Direct quenching will give highest attainable strength and hardness of core, with toughness lower than maximum; the case will be file hard, penetration hardness being with higher alloy steels somewhat below maximum, due to retention of austenite; excess carbide will be dissolved, and the embrittling effect of a network of grain-boundary cementite will be absent.

Most work subsequently to be water quenched is either slowly cooled from the carburizing operation or oil quenched to give some refinement to the core without danger of cracking or severe distortion.

Separate Hardening Treatments—As indicated in Fig. 2, several types of hardening treatments may be applied when work is reheated after cooling from carburizing, depending on whether case, core, or both are to be hardened. Most nearly approaching direct quenching is the use of a single reheat to a temperature higher than the critical point of the core (and of course, the case). Maximum core strength may be attained, with fair toughness; excess carbide in the case may be dissolved, and austenite will be retained in the higher alloy steels, although not as much as by direct quenching; distortion will be higher than by the latter method, but may be held within acceptable limits. This treatment, like direct quenching, is rarely applied to plain carbon steels.

Reheating to a temperature only above the critical point of the case may be employed either after slow cooling or quenching from carburizing.

Under the first of these conditions, the core will be soft and moderately tough due to the absence of any refining treatment; the case will be hard, but due to undissolved excess carbide, may be brittle; distortion will be low due to absence of core quench, but adhesion between case and core may be inadequate leading to easy spalling of case. If, however, the work has been direct quenched, a high degree of refinement results from this combination of treatments. The core is fully refined, having high toughness with low hardness; the case will be fully hardened, with good toughness due to absence of cementite as network; distortion will be considerable. Slow cooling from carburizing, followed by a reheat and quench from above the core critical temperature, and then a quench from above the critical point of the case, will give similar results but with the maximum possible refinement, coupled with a high degree of distortion. This latter treatment is historically the most important, the once universal "double quench."³ Present control of steels for grain growth characteristics, coupled with the demand for higher strength cores, and a realization of the futility of high core toughness and impact values, has rendered this treatment of declining use and interest.

A single reheating treatment may be carried on at a temperature above the case critical point but below the core critical point; with such hardening, the core is partially refined and quenched, the case slightly improved due to some solution of excess cementite. This is rarely used due to poor resultant over-all physical properties.

The reheating for hardening is sometimes preceded by a treatment at a sub-critical temperature, for example, 1200-1300°F., for a sufficient time to give partial coalescence and spheroidization of the proeutectoid cementite, thus reducing the tendency toward austenite retention in the subsequent hardening treatment.

Tempering—Internal stresses from quenching will be somewhat relieved and resistance to cracking in grinding operations improved by reheating the hardened work to the highest temperature (usually 275 to 350°) which will not appreciably reduce the hardness and wear resistance of the case. The tempering treatment is frequently omitted. Some stress relief is offered by any washing operation conducted at or near the temperature of boiling water.

Typical Applications—Gears constitute one of the most important type of parts to which the carburizing process is applied. Because of the high design loads in

bending and compression, case hardened gears are usually chosen for heaviest service. The design loads, theoretically high, may be tremendously increased if tooth profile or contact is improper, so that distortion is a prime consideration in selection of material and treatment for carburized gears.

Steel to be used will be chosen in accordance with the principles previously discussed. The required core physical properties determine the grade or amount of alloy, and the manufacturing and heat treating preferences determine the specific steel and processing to be used. Quenching is usually in oil, because water, and the more drastic media may cause an unacceptable amount of distortion. The plain carbon, hardening water types of steel are, therefore, rarely used, where distortion is an important factor, the majority of requirements being met by steels of the moderately alloyed class such as S.A.E. 3100, 4100, 4600, 5100 and 6100 series. When the highest core physical properties are demanded, the higher alloy types may be used.

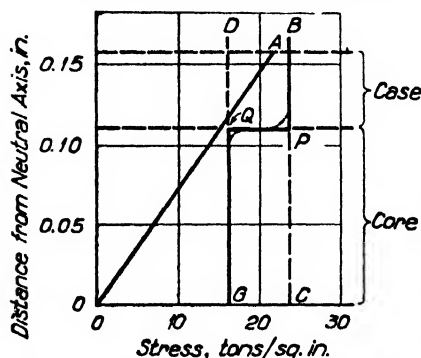


Fig. 1—Diagram indicating the fatigue range in carburizing steels (after Woodvine²).

From consideration of the stress diagram (Fig. 1) it is obvious that as higher stresses are imposed, resistance may be increased by increasing case depth (costly and, due to decreased tough core, embrittling) or by increasing core strength. Or, with constant stress conditions, increased core strength will permit reduced case depth. For this reason there is a growing use of higher carbon alloy steels for carburized gears, the case depth being reduced as is then permissible.

The shorter carburizing times make such procedures more economical. This combination of hard core and shallow case was also arrived at from consideration of the known advantages of cyaniding or otherwise shallow case hardening on the usual oil hardened gears of 0.35-0.50% carbon moderately alloyed steels. The shallow case required may be given by gas carburizing or cyaniding as a

simple extension of the normal heating cycle for hardening."

Since minimum and regular distortion is demanded in gears, steels with McQuaid-Ehn grain size of 5 or finer, usually 6 to 8, are customarily specified.

Annealing practice must be carefully controlled, a temperature of at least 50° above the subsequent carburizing temperature being used to insure full stress relief, and regulated cooling for best machinability is provided.

Hardening treatment should be selected in accordance with the previous discussion, the simplest treatments being preferable to give least distortion, but austenite retention must be held to a minimum, particularly when the gears are subject to high sliding loads such as in hypoid or worm gearing. Regulation of carbon content of case and of quenching temperature and velocity will assist in reducing austenite.

Camshafts—Selection of steel for such parts as these may be made in accordance with the principles previously discussed. Steels of the plain carbon and moderately alloyed types are used, surface hardness and wear resistance being a prime consideration. Since grinding after hardening is necessary, distortion must be kept low so that excessive straightening is not required. Careful annealing at a temperature well above carburizing temperature will aid in minimizing distortion. Hardening treatments employed are usually of the simple reheat type, shown as treatment "A" in Fig. 2, core properties being relatively less important than freedom from distortion. Quenching is frequently done in hardening machines wherein the piece is rotated while held in guides, thus holding straight enough that additional straightening is not required.

To facilitate straightening when necessary, areas of the shafts where the case is of no value may be protected during carburizing or the case removed therefrom by machining, so that after hardening these portions are ductile and permit bending as required.

Piston Pins—Steel for piston pins is selected on the same basis as for camshafts, the carbon and lower alloy types being most frequently used. In some cases, however, service loads may be sufficiently high that the use of higher alloyed steel may be demanded. Heat treatment should be selected as described above. Center

holes are often plugged to prevent carburizing inside with the consequent reduction of available thickness of tough core.

Spline Shafts—The principles already suggested apply to the selection of steel and treatment for spline shafts. The moderately alloyed types are preferred unless design loads demand greater stress resistance. Compressive load on the case due to pressure of the gear on the spline will govern the case depth required, while torsional and bending loads will determine core properties needed. Oil quenching is preferred for low distortion.

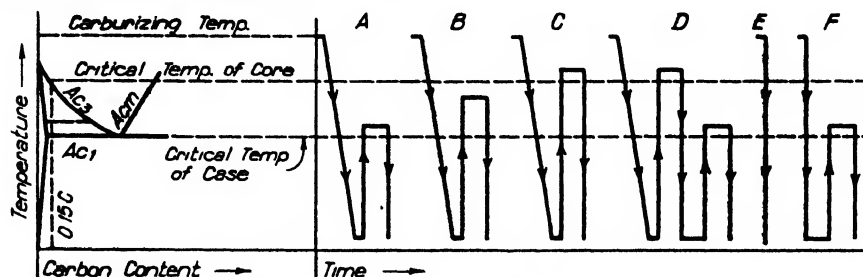


Fig. 2—Diagrammatic representation of various hardening treatments for carburized steels and summary of case and core properties⁸.

Treatment	Case	Core
A (Best adapted to fine grained steels.)	Refined; excess carbide not dissolved.	Unrefined; soft and machinable.
B (Best adapted to fine grained steels.)	Slightly coarsened; some solution of excess carbide.	Partially refined; stronger and tougher than (A).
C (Best adapted to fine grained steels.)	Somewhat coarsened; solution of excess carbide favored; austenite retention promoted in highly alloy steels	Refined; maximum core strength and hardness. Better combination of strength and ductility than (B).
D (Best treatment for coarse grained steels.)	Refined; solution of excess carbide favored; austenite retention minimized.	Refined; soft and machinable; maximum toughness and resistance to impact.
E (Adapted to fine grained steels only.)	Unrefined with excess carbide dissolved; austenite retained; distortion minimized; file proof when carbon is high.	Unrefined but hardened.
F (Adapted to fine grained steels only.)	Refined; solution of excess carbide favored; austenite retention minimized.	Unrefined; fair toughness.

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Pack Carburizing

By H. W. McQuaid*

Chemical Reactions—With solid carburizers, nascent carbon is formed, on the surface of the steel, by the decomposition of carbon monoxide into carbon and carbon dioxide. The carbon dioxide formed reacts immediately with the incandescent carbon in the compound to form fresh carbon monoxide. This process is repeated as long as there is ample incandescent carbon present to react with the excess of carbon dioxide. The decomposition of carbon monoxide occurs at the surface of the steel which must be at such a temperature that the nascent carbon formed will go into solution in the steel itself.

Carburizing Compound—The usual commercial carburizing compound contains a mixture of approximately 20% alkaline or metallic carbonates bound to a hardwood charcoal by the use of oil, tar or molasses. This carbonate energizer is generally in the form of barium carbonate with occasionally a small percentage of sodium and calcium carbonate. There is usually added approximately 20% of coke as a diluent. The presence of the coke increases the rate of transfer of heat through the compound and hence is of value in obtaining uniform temperatures.

Because of the loss of the carbonate energizer, the powdering of the compound, and the burning in service, new compound is added before using again. It is necessary to have approximately 8% of the carbonate energizer present in the mixed compound. A percentage greater than this has little effect on the rate of carburization, whereas a decrease in energizer much below 8% retards the carburizing action and decreases the maximum surface carbon content. The addition of new compound will vary according to the care used in handling, the amount of direct quenching which is done, and the type of binder used in the compound. If care is used in the selection of boxes and the handling of the compound it is possible in most plants to use at least five parts of old with one part new compound, and some plants are operating with smaller additions of new than this. In many plants, however, the conditions are such that more new compound is required and it is not unusual to find plants making an addition of one part new compound to three parts used compound.

There are available carburizing compounds which do not consist essentially of charcoal with a carbonate energizer. Carburizing compounds have been made from various combinations of organic materials such as charred leather, burnt bone, raw bone, bone or bone with charcoal. These compounds will give satisfactory results when properly applied. They are relatively expensive and if no energizer is used their carburizing action is slow. Large quantities of bone black compound containing a relatively low percentage of energizer have been used for applications where low carbon cases are desirable. There have also been large quantities of carburizing compound used in which a water soluble energizer has been impregnated in a very dense charcoal. These compounds will usually give satisfactory results.

Recently compounds have appeared on the market which vary greatly from the standard in that they do not use charcoal but substitute a special type of coke. Other compounds have been developed which do not use a carbonate type of energizer.

Selection of Carburizing Compound—In selecting a carburizing compound there are many factors to consider. The handling equipment is an important factor as well as the quenching methods. With work cooled in a well designed box where the compound is not subject to exposure to air while at a red heat, it is not necessary to give much consideration to the burning characteristics. Where there is much quenching from the box, the rate of burning is an important economic factor and should be considered in selecting a compound.

Since the amount of new compound used is determined by the energizer retained by the used compound the method of incorporating the energizer is of importance. The cost of a compound should be based on lb. of satisfactory work per lb. of compound per hr.

The coated compound is at a disadvantage when compared to the impregnated compound except where handling and cooling conditions are exceptionally favorable.

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Prepared for the Subcommittee on Carburizing. The membership of the subcommittee was as follows: R. B. Schenck, chairman; E. F. Davis, J. A. Dow, R. W. Schlumpf, H. W. McQuaid, and G. T. Williams.

If, however, no attempt is made to take advantage of a more stable compound by increasing the ratio of used compound to new, then the more expensive compound is of little advantage.

Packing—The packing of work in the compound is a dusty and somewhat disagreeable operation. For this reason the grouping of boxes, work, and compound should be carefully worked out to provide a minimum of compound handling. The work should come to the packer, if possible, already stacked and sorted, preferably on open trays or in pans.

A small layer of compound is first put in the empty box. This layer should be approximately one in. in depth although with lighter work this can be reduced to $\frac{1}{2}$ in. The minimum amount of compound should be used and this depends on the design of the box and the type of work. If the boxes are warped badly, more compound must be used on the top to prevent exposure of the work by burning away of the compound. Ordinarily, with alloy boxes, much less compound can be used than is common practice. The compound is a most excellent heat insulator while the metal is a very good conductor. Therefore, any increase in compound over the minimum necessary to support the work will result in an immediate and important increase in heating time. An increase of $\frac{1}{2}$ in. in compound between the work and the wall of the box is equivalent to increasing the wall thickness by many inches.

It is the usual practice to remove the dust and fine particles by screening, and between rough handling and the screening a large percentage of energizer and charcoal is wasted. The ordinary coated charcoal compound is extremely friable and must be handled with great care. If due attention is given to this problem the amount of compound used can be greatly reduced. Some of the conveyors, storage arrangements, and cleaning devices destroy so much carburizing compound that they become a liability rather than an asset.

Carburizing Boxes—While heat resisting alloy boxes have become quite standard, there are still many applications where rolled steel or cast steel boxes have an advantage. The heat resisting alloy boxes are usually made from a nickel chromium combination. The heat resisting alloy can be obtained either in the sheet form or as a casting. Both types have their advocates. The cast form is generally the least expensive especially where boxes are of a nonsymmetrical design. It is possible to obtain the cast boxes with a wall thickness which compares favorably to that of rolled sheets, and because of this there has been a general tendency toward a reduction in thickness of the walls of cast carburizing containers. The sheet alloy boxes are generally used for cylindrical shapes and have proven quite successful in these applications providing the welding is properly done. A large percentage of the failures with the sheet alloy boxes has been caused by poor welding.

Before a decision is made to use heat resisting alloys for carburizing boxes, a careful investigation should be made to determine the services expected from the containers. For boxes which are infrequently used and especially where the work being carburized is large and nonsymmetrical in section, cast steel or welded steel plate often prove more economical than the much higher priced alloy boxes. As a rule, however, where boxes are frequently used and the shape and size of the pieces do not require boxes of excessive size, the best heat resisting alloy will prove economical.

The design of the box* and the method of packing influence the carburizing results. Whenever possible work should be packed with its longest dimension vertical. This is an important requirement with shafts and stem pinions. Vertical packing permits vertical quenching with the least tendency of the tongs to distort the hot work.

Uniform heating is important and therefore the cylindrical box is to be preferred to rectangular boxes where the corners heat at a different rate than the sides, and where the work in the corners comes to heat before work in the center. Center tubes should be used wherever possible. These can be designed as integral with the box or where they must be removed to facilitate handling the work they can be separate.

Carburizing Temperatures and Case Depths—For steels of the fine grained type a carburizing temperature of 1675-1700°F. will be satisfactory. There are, however, many carburizing furnaces operating at 1725°F. or even 1750°F. with good results. These are usually continuous furnaces with carefully controlled cycles.

*R. W. Rousch and A. C. Dames, A Study of Commercial Carburizing Containers, Trans., A.S.M. v. 26, 1938, p. 646.

For some steels, especially the higher nickel alloy steels, lower carburizing temperatures are used. These steels use a temperature of 1625-1650°F. The same temperature is used in some plants to reduce warpage to a minimum. For work having a small section where the case depth must be controlled to a maximum of a few thousandths still lower carburizing temperatures are employed, and in some applications 1550°F. is used with a bone-base compound low in energizer.

Even with the best of furnaces and practice at 1700°F. it is difficult to obtain a total variation from maximum to minimum in a given furnace load of less than 0.010 in. in case depth. Pack carburizing is at a disadvantage in producing a case depth of less than 0.025 in., unless boxes are properly designed and work scientifically packed to eliminate temperature variation. With the standard practice of today case depths of less than 0.025 in. should not be specified for pack carburized work. For these light cases a carburizing temperature of 1625-1650°F. is suggested.

It is difficult to control the maximum carbon content in the case of a packed carburized part. Since the rate of evolution of carburizing gas in pack carburizing is fixed and is practically always in excess of the amount required to supply the necessary carbon for a saturated surface, it is customary in pack carburizing to obtain a saturated outside surface layer. If the energizer is deliberately controlled to reduce the carburizing effect, which can usually only be conveniently done in a bone compound, it is possible to obtain cases lower than the maximum which would be obtained under ordinary conditions at the carburizing temperature. The total carbon above the eutectoid will be greater as the carburizing temperature increases, but the maximum surface carbon will increase as the carburizing temperature decreases. This is because the solubility of the steel for carbon increases with increasing temperature. At low carburizing temperature the surface becomes supersaturated with carbon because of the inability of the carbon to diffuse.

Furnaces for Pack Carburizing—The fundamental requirement of pack carburizing is the elimination of variables which affect the temperature of the work. The first problem is to secure a furnace that can be controlled to plus or minus 10°F. and which heats uniformly throughout within 20°F.

As a rule, a furnace with the hearth at floor level is to be preferred, although there are exceptional cases where the hearth is more conveniently located at some distance above the floor. If the furnace is to be used for carburizing only and especially if the loaded boxes are of an appreciable size, the floor level furnace is much to be preferred. When quenching from the carburizing temperature, the floor level furnace has the advantage of minimum handling of the hot boxes.

Many of the so-called "standard" box type furnaces on the market, especially those built for oil fuel, are unsuitable for carburizing because of the great variation in temperature from one point to another. This type of furnace is especially apt to be low in temperature near the door and high in temperature at the back. When this difference is known it is often compensated for by putting work requiring a deep case in the back of the furnace and the lighter cased work in the front.

Where the volume of work will permit, a pusher type continuous furnace is desirable. The economical justification of this type furnace is closely related to box design and depth of case required. Where case depth is not too great and where boxes are designed to reduce the heating time to a minimum the continuous pusher type furnace has a great many applications. By careful attention to box design it will be found that the case depth can be held to reasonably close limits over a wide variation of work size. This requires careful attention to insure a reasonably close uniformity of work temperature at the time carburizing begins which usually means a temperature of approximately 1500°F. By using a minimum of carburizing compound the over-all carburizing time can be reduced to a minimum and a wide range of commercial work can be carburized to a 0.040-0.050 in. depth in nine hours or less in the furnace at 1700°F. A total of nine hours time in the furnace means that approximately five hours are used in bringing the work to 1700°F. since a case depth of 0.040-0.050 in. will be obtained in four hours at 1700°F.

A nine or ten hour cycle in a continuous pusher furnace 16 ft. long using two rows of 10 in. diameter containers should give approximately the same production as three of the usual type furnaces having a clear hearth area of 16 sq. ft.

The continuous furnace will produce more uniformly heated work, will lower fuel and container cost, and probably give less trouble due to variable case depth. The actual cost depends on the container design, the ability of the mechanical handling device of the continuous furnace to stand up, and the heating characteristics of the continuous furnace.

Gas Carburizing

By J. A. Dow*

Chemistry—In gas carburizing the carbon to be supplied to the steel is introduced to the work chamber, or retort, of the furnace in a gaseous state, rather than in a solid form which yields the desired gases on heating. For an understanding of the subject it is unnecessary to consider the reactions involved to be other than simple chemical reactions between gaseous compounds of carbon, and iron. Carbon is available in the gaseous state as carbon monoxide and as hydrocarbons, such as methane, ethane, propane, and butane, present in varying percentages in commercial fuel gases.

These hydrocarbons break down at carburizing temperatures almost completely to carbon and hydrogen if given sufficient time. This rate of breakdown, in terms of carbon liberated, is the maximum when the hydrocarbon is undiluted, and the minimum when the hydrocarbon is highly diluted by hydrogen or other gases. All the gaseous hydrocarbons will break down, if used undiluted for carburizing, at such rate as to liberate an excessive amount of carbon in the form of soot or coke on all exposed surfaces, in addition to the carbon combining with, or dissolving in the steel. If highly diluted, the rate of reaction with the steel is slow as compared to the possible rate of carbon diffusion into the steel, and the result is a low carbon and relatively shallow case in a given time. With increasing concentrations of hydrocarbon in a carburizing gas an upper limit in carburizing rate is reached, this limit being apparently the maximum rate at which carbon will diffuse into steel at the temperature used. Increases in hydrocarbon concentration beyond this point result in increasing free carbon deposit.

For uniform carburizing it is necessary to maintain in all parts of the furnace work chamber, either an uniform concentration of hydrocarbon gas or concentrations above that which produces the maximum rate of carburizing. High hydrocarbon concentrations, on the other hand, cause deposition of free carbon in a state and quantity which impedes further interaction of the gaseous carbon compounds and the steel, and cause shallow or spotty cases.

Certain gases, such as most natural gases, permit concentrations of hydrocarbon considerably above the minimum necessary for active carburizing without damaging carbon deposition. It is possible to feed these gases undiluted into the furnace retort, sufficient dilution being obtained by the mixing which immediately occurs with the partially spent, or stale, gas in the carburizing chamber. When using this method, sufficient feed of carburizing gas must be maintained to produce active carburizing at points in the retort farthest from the gas inlet. This minimum rate of gas feed may at the same time, however, cause high hydrocarbon concentration and excessive carbon deposition near the gas inlet. Where no provision is made for agitating the gas, or otherwise obtaining an uniform analysis throughout the chamber, there is a limit in the size of the furnace in which this method can be used.

Because of the gradual reduction in the hydrocarbon concentration of the gas as it passes through the retort when using this simple method, the case produced, when uniform throughout the charge, is usually a high carbon type undesirable for some parts. To overcome this, many plants have successfully adopted a method suggested by Day,¹ and Bramley and Lord² and described by Williams,⁴ and by Gable and Rowland.⁵ A period of diffusion following the carburizing, with no gas being introduced into the retort, permits the carbon to diffuse into the steel until the surface carbon content has dropped to the desired figure.

A variation in this method, having considerable merit, is to make the carburizing cycle a succession of carburizing and diffusion periods. This and a further modification by Guthrie and Wozasek³ are both described by Williams.⁴

For the heavier hydrocarbon gases, which break down under heat too rapidly to permit the use of the above method in its simplest form, and for controlling the carbon content of the case produced without the otherwise necessary diffusion period, and for better operation of continuous furnaces, many diluting gases have been developed with the object of controlling by dilution the rate at which carbon is liberated from the hydrocarbon source of carbon. These gases in many cases

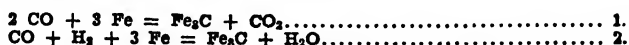
*Engineer, Holcroft & Co., Detroit. Prepared for the Subcommittee on Carburizing. The membership of the subcommittee was as follows: R. B. Schenck, Chairman; E. F. Davis, J. A. Dow, R. W. Schlumpf, H. W. McQuaid, and G. T. Williams.

complicate the chemistry in the furnace, and can be divided into two general classes: those gases which contain decarburizing agents and those which do not.

The various gases which are introduced into carburizing retorts can be classified under headings as follows:

Carburizing Gases	Decarburizing Gases	Neutral Gases
Carbon monoxide, CO Methane, CH ₄ Ethane, C ₂ H ₆ Propane, C ₃ H ₈	Carbon dioxide, CO ₂ Water vapor, H ₂ O (oxygen burns to produce the above gases in the retort)	Hydrogen, H ₂ Nitrogen, N ₂

Carburizing Gases—1. Carbon Monoxide—Carbon monoxide carburizes by the mechanism of the two following reactions:



It will be noted that in giving up carbon to the iron an active decarburizing agent is in each case produced. Moreover the reactions are reversible. Both reactions proceed rapidly but liberate only a small amount of carbon before their equilibrium is reached and the reaction stops.

For this reason carbon monoxide can be considered an active carburizing agent, yet having only a small amount of carbon available per cubic foot of gas. Hence, carbon monoxide as a commercial carburizing gas is limited to the "skin" case hardening of medium carbon steels. It is, however, an excellent gas for diluting the heavier hydrocarbons, its action being for practical purposes in this case a neutral diluent. It does not introduce complications into the retort chemistry.

2. Methane—Methane is the slowest of the hydrocarbons in its rate of breakdown under heat, and for this reason is the most easily controlled. Where unaided by other hydrocarbon gases in small quantities, and when diluted by inert gases only, the methane concentration must be 40% or better to produce active carburizing at 1700°F. This concentration must be higher at lower temperatures and vice versa.

Methane can be considered a sluggish reacting gas carrying in the concentrations necessary for carburizing, a large amount of available carbon per unit of volume.

3. Ethane and Propane—Ethane and propane are alike in their behavior. Both break down rapidly at carburizing temperatures, and in concentrations above approximately 1% in neutral diluents, will deposit free soot on the work. These gases can be considered rapid-reacting gases carrying only a moderate amount of available carbon per unit of volume when mixed with neutral diluents in the proportions for best carburizing.

Ethane is present in almost all natural gases in varying percentages, while propane is available in a very pure state in liquid form.

Decarburizing Gases—Both carbon dioxide and water vapor are active decarburizing gases. They decarburize according to reactions (1) and (2) above, and when present in concentrations above 0.2% in the average carburizing gas mixture at 1700°F. tend to remove carbon from the steel. This decarburizing tendency can only be overcome by a concentration of hydrocarbon considerably in excess of that required for active carburizing when diluted by neutral gases only. For example, active carburizing is obtained from 1% of propane in neutral diluents, whereas, concentrations of this same gas up to 30% in the mixture fed to a furnace, have been found necessary to produce an equivalent result when the diluting medium contained approximately 2-3% of water vapor and carbon dioxide. When these gases are introduced to a carburizing chamber along with hydrocarbon gases, a rapid interaction of the two types of gas takes place, resulting in the disappearance of the decarburizing agents and the formation of carbon monoxide and hydrogen.

Neutral Gases—Atmospheric nitrogen does not apparently enter into any of the reactions of carburizing.

Hydrogen has been considered by many authors as an active decarburizing agent. To decarburize, hydrogen must combine with carbon according to the following reaction: $\text{C} + 2 \text{ H}_2 \rightarrow \text{CH}_4$

Since 2-3% of methane in a gaseous mixture prevents this reaction proceeding it is nonexistent in all gas carburizing.

Carburizing with Gaseous Mixtures Containing Decarburizing Gases—The diluting media of this type are the products of partial combustion of the hydrocarbon

gas and air, produced either in a separate gas generator, or in the furnace retort itself by the introduction of gas-air mixtures. If this combustion is carried out in a separate chamber it is the usual practice to condense out much of the water vapor formed, and to maintain as nearly as possible a constant analysis, with particular emphasis on the carbon dioxide and water vapor contents.

Two types of gas preparation units are in common use. They differ only in that the one type makes use of an externally heated retort or bank of tubes as a cracking chamber and can be operated with a richer gas-air mixture than the second type wherein the heat required for cracking the gas is supplied by the gas-air mixture itself, fired directly into a fire brick lined combustion chamber. A wider range of gas analyses may be obtained from the first type, whereas, it is difficult to produce a gas containing less than 4% carbon dioxide from the latter style. For carburizing, this prepared gas is mixed with natural gas or propane and fed to the carburizing chamber.

Another method in common use is to feed mixtures of propane and air, or natural gas and air directly to the carburizing chamber. In this instance, combustion immediately consumes the limited amount of air present, leaving a gaseous mixture containing the excess propane, or natural gas, and rather large percentages of the decarburizing gases, carbon dioxide, water vapor, and nitrogen.

The rate at which this type of gas mixture liberates carbon to all surfaces changes in its passage through the carburizing chamber, first increasing while the decarburizing agents are being removed by chemical interaction with the hydrocarbons, then later decreasing as the hydrocarbons are used up. It is possible with such a mixture to have slow carburizing near the gas inlet, a coke (carbon) deposit at the point of greatest activity, and slow carburizing in places remote from the inlet. Uniform carburizing throughout the work chamber may be obtained if sufficient hydrocarbon be used to overcome the effect of the decarburizing gases near the gas inlet, and a total volume of mixture adequate to supply the parts distant from the inlet. It is difficult with these mixtures to obtain uniform carburizing with other than high carbon cases unless provision be made for subsequent diffusion. Undesirable carbon deposition on the stock usually accompanies this method of carburizing.

Table I gives a list of gaseous mixtures of this type which have been used commercially. Multiple gas inlets with the rate of feed and composition different at the various inlets have given best results on larger furnaces, particularly of the continuous type. Carburizing with manufactured gas falls into this classification because of the presence of carbon dioxide and water vapor.

Table I
Gaseous Carburizing Mixtures Containing Decarburizing Gases

Carburizing Gas	Diluent Gas Analysis, % by Volume								% Carburizing Gas in Mixture*
	CO ₂	O ₂	H ₂ O	Illuminates	CO	H ₂	CH ₄	N ₂	
Natural Gas.....	4.5	0.0	2.5	....	8.0	9.0	0.5	Bal.	40
Natural Gas.....	0.4	0.3	2.5	0.3	15.8	30.1	15.0	Bal.	45
Propane				Air					33½
Propane	3.5	0.0	2.5	1.5	16.2	20.4	6.0	Bal.	20
City Gas	3.0	0.6	(dried)	4.3	12.1	44.6	29.8	5.6	

*These examples are taken from furnaces with multiple inlets and the figures in this column are based on the total gas fed to the furnace. The mixture, however, varied considerably from inlet to inlet.

Carburizing with Mixtures of Hydrocarbon and Neutral Gases—Dilution media of this type consist of the gases nitrogen, hydrogen, and carbon monoxide, with only minute quantities of carbon dioxide and water vapor present, and containing in some cases methane in percentages too low to have an appreciable carburizing effect.

When produced in a separate gas generator, a combusted gas-air mixture or straight air is passed through a heated bed of charcoal, wherein the carbon dioxide and water vapor react with the charcoal to produce carbon monoxide and hydrogen.

Another method in commercial practice is to use as the diluent medium the partially spent gas which issues from the gas outlet of the carburizing chamber. This partially spent gas is normally free of decarburizing agents and need be only slightly enriched by an addition of hydrocarbon and returned to the retort.

Carburizing with natural gas, or other pure hydrocarbon fed to the furnace in an undiluted state falls under this classification of carburizing since the spent gas

in the retort acts as a diluent to the incoming gas. Intermittent feeding of the gas addition at high velocity aids in producing thorough mixing and uniform hydrocarbon concentration throughout the chamber.

When using this type of diluting gas only two considerations enter into the control of the carburizing. (1) Sufficient dilution of the hydrocarbon gas fed to the retort must be used or obtained by agitation, to prevent excessive carbon deposition near the gas inlet and to maintain reasonably uniform gas analysis throughout the chamber. (2) The hydrocarbon addition is varied to produce the type of case desired.

High gas velocities have not resulted in nonuniform carburizing with this type of gas mixture.

Multiple inlets are an aid, reducing the amount of diluent gas necessary, where the carburizing agent is ethane or propane, but are not apparently necessary where methane is the principal carburizer except on large furnaces.

Light cases of from 0.005-0.015 in. in depth are being produced at temperatures of 1500-1550°F. in from 1-2 hr. total time in the furnace, with excellent control of case characteristics, by approximately 1% of propane or ethane in a dilution medium prepared from charcoal as described above. This type of gas carburizing is being used to replace cyaniding. Parts so treated come from the furnace entirely free from scale or soot.

Commercially Available Hydrocarbon Gases—Natural Gas—Natural gas consists chiefly of methane with ethane varying between 5-20%. For carburizing purposes it can be considered a hydrocarbon mixture, for practical purposes, free of decarburizing agents and containing but small percentages of neutral diluents. Sample analyses are given in Table II.

Table II
Analyses of Natural Gas^a
% by Volume

	CO ₂	O ₂	Illuminates	CO	H ₂	CH ₄	C ₂ H ₆	N ₂
Cleveland	0.2	0.2	0.8	..	80.7	18.0	0.5
Detroit	0.1	0.4	..	..	..	76.0	14.0	2.5
Pittsburgh	83.4	15.8	0.8
Canton, Ohio.....	..	1.2	0.8	1.0	..	79.2	16.1	1.7
Columbus, Ohio.....	..	0.2	..	0.8	..	80.7	17.0	1.5

Natural gas is to be preferred for gas carburizing because of its relative purity and because the high content of the rather sluggish reacting methane makes the gas easy to control.

Propane—Propane is obtainable in a pure state, bottled under pressure as a liquid which gasifies immediately under reduced pressure. (See article in this Handbook on Liquefied Petroleum Gases.) For carburizing purposes propane from the natural gas fields is to be preferred to that made at oil refineries. The latter type contains a rather high percentage of propylene which in certain gas mixtures deposits undesirable coke (carbon).

Because of its purity propane is a very satisfactory carburizing medium and is to be preferred to the gases listed below.

Butane—Butane is marketed in a manner similar to propane and is only being used for carburizing where it is also the fuel used for heating. It is quite sensitive to handle in carburizing and usually covers the work with heavy carbon deposits.

Manufactured Gas—Manufactured gas can have a wide range of analyses, depending on the method of its manufacture, and in most places a mixture of two types is supplied by the utility company, the proportions of each varying with the gas load.

For this reason and because of the rather high carbon dioxide and water vapor and low hydrocarbon content, manufactured gas is being used for carburizing in few places. To obtain active carburizing it is often necessary to either partially dry the gas or to enrich it with propane. Control is difficult because of the varying analysis. Manufactured gas is however quite satisfactory for making a diluent gas by some of the methods described, particularly the charcoal gas type, in which case propane as the enriching agent becomes a negligible item in operating costs even though purchased in bottles.

Composition of Manufactured Gas

% by Volume

	CO ₂	O ₂	Illuminates	CO	H ₂	CH ₄	C ₂ H ₆	N ₂
Coke Oven Gas	1.8	0.6	3.0	18.0	53.1	18.4	..	5.1
Carburetted Water Gas..	6.2	0.6	9.3	24.0	43.3	11.9	0.4	4.3

Furnace Types—Batch Type—Horizontal, rotating retort type furnace, gas or electrically heated, is used when suitable for parts which are not injured by the tumbling action which takes place during the operation. Because of the simplicity of the retort section and the absence of trays and fixtures this method of carburizing is the most economical. The tumbling action continuously removes soot from the parts, making the operation less sensitive to high hydrocarbon concentrations. Fixtures can in some instances be used for work which would be battered by the tumbling.

The vertical retort type, gas or electrically heated furnace, with and without means of mechanical agitation of the gas in the retort, produces uniform carburizing by regulation of gas mixtures, flow, and by the location of gas inlets. Mechanical agitation of the gas in the retort is sometimes used in this type of furnace. If satisfactorily applied, it eliminates rate of gas input as a factor in producing identical cases throughout the charge. This type is being built for operation with certain liquid hydrocarbons as the source of carbon.

In the horizontal stationary retort type, gas fired furnace, the work is carried on trays and fixtures and because of the size of the furnace a diluting gas is normally used. The retort life is greatly affected by the thermal shock due to the heavy charges of cold stock.

Continuous Type—Continuous gas carburizing furnaces are all of the pusher tray type. The work is carried on fixtures or trays, and may be built for automatic quenching, for hand quenching, or for slow cooling in a cooling zone built onto the discharge end of the carburizing zone.

Operating costs on these furnaces are usually considerably lower than with continuous pack carburizing furnaces when operated at close to capacity. The hourly operating cost however is almost as great when running at half capacity as at capacity. Design, and soundness and cleanness of the alloy in the muffle, trays and fixtures are important factors in costs.

Notes on the Operation of Gas Carburizing Furnaces—Case variation can be divided into three classes: (1) The variation which occurs on parts at different locations in a batch furnace, or in a cross section of the muffle in a continuous furnace. (2) The variation which occurs from heat to heat or day to day. (3) The variation in case on protruding and recessed surfaces of a single piece, or on the exposed and unexposed surfaces of parts stacked closely together.

1. The first type of nonuniform carburizing can be caused by temperature variation, which is a common occurrence in batch furnaces because of the difficulty of designing for door and end heat losses. The only other cause of this type of case variation is a gas of varying analysis throughout the work chamber.

If no diluting medium is being used, an increase in gas flow, additional gas inlets, or agitation of the gas in the furnace by intermittent feed or some form of mechanical circulation either inside the furnace or by a return pipe and gas booster outside the furnace will overcome this type of case variation.

If a diluting medium containing decarburizing agents is being used, the remedy depends on the location in the furnace with respect to the gas inlets of the zone of light cases, and has been previously discussed. This type of case variation due to varying gas analysis in the chamber rarely occurs when a diluting medium free from decarburizing gases is used providing there be adequate total flow.

Retort leaks can be the cause of a varying gas analysis in a carburizing chamber with all gas carburizing methods.

2. The case variation which occurs from day to day or heat to heat, may be caused by: (a) Change in the analysis of the carburizing or diluent gas. (b) Change in the condition of the muffle or other furnace alloy. The hydrocarbon gas fed to a furnace may have to be increased 50% or more above normal to overcome an oxidized muffle condition. Forty-eight hours may be required to completely condition an oxidized or new muffle. (c) The control thermocouple losing its accuracy.

3. The third type of case variation, heavy cases on protruding surfaces and light cases in recesses, is apparently more a function of the hydrocarbon concentration in the carburizing chamber than any other factor and may best be overcome by increasing the rate of feed of hydrocarbon. Where this variation occurs on the adjacent sides of adjacent parts it may be advisable to separate the parts somewhat more inasmuch as an increase in hydrocarbon feed usually causes somewhat dirtier stock.

An intermittent or on and off gas feed may be of help in remedying this condition.

No form of gas circulation can produce equal scavenging of spent gas from protruding and recessed surfaces, nor is apparently much of a factor in this type of case variation.

With equal tendencies to deposit soot and with other conditions constant, the higher the content of sluggish reacting methane in the carburizing gas in the retort, the better will be the uniformity of carburizing on exposed and recessed areas. Oil vapor, if it gets into the gas in the retort, works opposite to methane and causes bad case variations.

The formation of tar in a gas carburizing furnace which is indicated by coke (carbon) deposit on the work can best be corrected by the reduction in the rate of hydrocarbon feed. In batch operation it is advisable after an initial flushing of the retort to shut the gas off until the charge is fully at heat. Additions of water vapor, carbon dioxide, or air to the hydrocarbon gas seem to cause a greater reduction in the carburizing power of the gas than in the tendency toward tar formation. Oil in the pores of the alloy trays used in a continuous furnace has contributed to tar formation. Butane, and refinery propane containing propylene, are more difficult to handle in this respect than natural gas or the purer form of propane obtained from natural gas. A gradual increase in the hydrocarbon concentration of the gas in a furnace retort occurs in many instances for several hours after the gas is first turned on and can result in tar formation some hours after the start of the operation. A reduction in gas feed corrects this condition. Sulphur, if excessive in the muffle gas, can act as a powerful deterrent to carburizing.

A decarburized surface of a few ten-thousandths of an inch in thickness, and detectable with a file, can be produced almost instantly if work is allowed to stand in a decarburizing atmosphere just before quenching. The life of furnace muffles, trays and fixtures, is more a function of the cleanness of the metal and the soundness of the casting, and design, than of the nickel and chromium content of the metal.

Welds have not proven satisfactory where subjected to the action of carburizing gases.

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Liquid Carburizing

By E. F. Davis*

Introduction—For many years chemical salts such as cyanides (prussiates) have been employed to impart a hardenable surface on wrought iron and low carbon steel. These were first used as powders and used in a blacksmith forge, but later immersion methods were installed whereby the parts were dipped into a molten bath and allowed to acquire a superficial case which would subsequently become file hard by quenching in water or oil.

Cyanide of sodium or potassium were usually preferred and have proved fairly satisfactory for case depths up to 0.010 in., but evidently the nitrides formed on the surface at low temperatures become an obstructing agent preventing rapid diffusion of the carbon so that the penetration rate is much reduced after an initial case of 0.004-0.0065 in. is formed. Although it is possible to carburize to any depth in cyanide alone, if the process is sufficiently prolonged, such a slow method is commercially impractical.

Development of Activated Baths—The early experiments employing the addition of an activating agent to a neutral or noncarburizing bath were for the purpose of utilizing the infusible calcium cyanamid. This was first exemplified by the German Deininger process, and later in this country by the Shimer process. These methods consisted of adding calcium cyanamid at intervals to a molten bath composed of a mixture of calcium and sodium chloride. In the Shimer process it was deemed necessary to submerge the cyanamid below the surface by means of a small metal basket containing the lumps of cyanamid. The bath was "re-activated" from time to time by replacing with fresh cyanamid. Later this process of submerging was eliminated by improvements in the method.

Types of Activated Baths—Both in Europe and the United States a number of activated bath formulae have been developed during recent years, utilizing, in addition to calcium cyanamid, polymerized hydrocyanic acid, or sodium or potassium cyanide with controlling chemicals. Controlling chemicals refer to certain salts such as fluorides or special catalysts which govern the decomposition of the cyanides. The latter type of bath has all the various constituents fused together and cast into lumps or coarsely powdered, and requires no additions at intervals of a separate activating material.

Carburizing with Activated Baths—The case depth limits that are most economical are generally placed between 0.010 and 0.030 in. Above 0.030 in. it is usually more cheaply done by standard pack or gas carburizing processes; hence its greatest field of utility is the gap between cyaniding and furnace carburizing where a closely controlled case is necessary, such as parts of thin section where the allowable variable is quite small. Variations as close as 0.003 in. can be obtained consistently.

When deep cases are obtained in activated baths the consumption of fuel is increased abnormally and pot life per ton of steel carburized is much reduced. If the temperature is increased to shorten the time, pot life is correspondingly lowered.

Temperature of Carburizing in Activated Baths—Most baths are operated between 1500 and 1650°F. The lower temperatures are usually employed when only a superficial case is desired similar to the cyaniding. Investigations by B. B. Beckwith† have shown little variation in ultimate results obtained from six different commercial activated compounds when the parts were treated under the same conditions of time and temperature. The reason for this is no doubt due to the fact that steel possesses definite rates of absorption and diffusion of carbides in accordance with the temperature attained, and is not influenced to any great extent by the richness of the carburizing agent at the surface.

Character of Case from Activated Baths—The character of the case in activated baths is different from that of cyanide. As a rule the case is richer in carbides and

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Prepared for the Subcommittee on Carburizing. The membership of the subcommittee was as follows: R. B. Schenck, chairman; E. F. Davis, J. A. Dow, R. W. Schlumpf, H. W. McQuaid, and G. T. Williams.

†B. B. Beckwith, Liquid Bath Carburizing, Trans., A.S.M., 1938, v. 26, p. 752.

contains from 50-75% less nitrides. Nitrides are however present to some extent in the case obtained from nearly all the baths now in operation. However, nitrogen needles are seldom found in the carburized area of parts treated in activated baths, hence may lead to the belief that nitrides are absent. However, analysis of the layers of the case will show that some nitrides are present. These may vary from 0.05-0.30% in the outer zones. Another difference between the cyanide and activated case is that it is possible to obtain eutectoid and hypereutectoid case from these mediums and in composition resembles more the carburized than the cyanided case.

Advantages of Activated Carburizing—The case obtained from activated baths is less brittle than the cyanided due to less nitrides. Where a brittle case is objectionable, activated carburizing is often preferred. The activated case also tempers or softens more easily than the cyanided.

The presence of small amounts of nitrides in the activated case is really an advantage because it enables parts of thin section such as stampings, washers, small gears and other parts of small area to be file hard by an oil quench. A large percentage of these parts are made of S.A.E. 1010, 1020, 1120 and similar carbon steels, which otherwise might require a water quench to produce the necessary hardness. Oil quenching reduces the tendency toward brittleness and distortion.

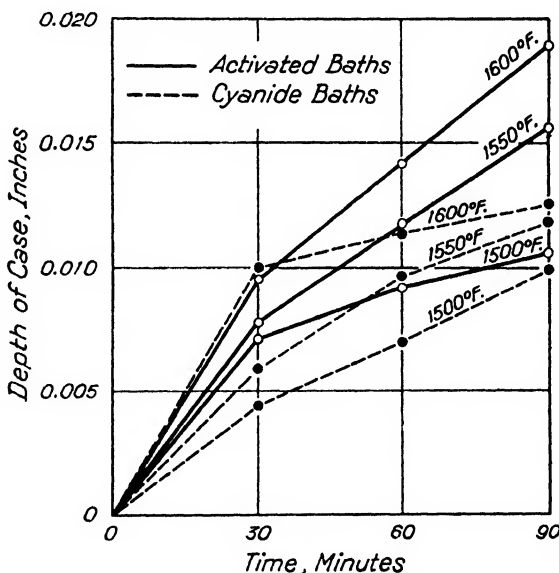


Fig. 1—Case Depths for Activated Baths and Cyanide Baths. (Beckwith)

Furnaces for Activated Baths—Pot furnaces are used with cast steel, heat resisting alloy, or welded plate. The furnaces are either gas, oil, or electric fired. Where internal electrode heating is used on the activated baths no deterioration of the salt has been reported.

Requirements of an Ideal Activated Bath—1. No infusible residue should accumulate to contaminate the bath. 2. It should not require constant attention to keep it in operating condition. 3. It should not be sensitive to contamination with other salts used in heat treating operations. 4. It should be fluid and drain off readily when the parts are lifted out of the bath to keep take-out losses to a minimum. 5. It should be economical in price based upon volume weight molten. 6. It should wash from the parts readily. 7. It should carburize uniformly at all times. 8. It should not foam badly or corrode containers. 9. It should not be a health hazard to workers. 10. It should not produce excessive fumes at operating temperatures. 11. It should not promote rusting of parts. 12. The decomposition rate requiring additions of fresh salt should approximate the amount of loss by drag-out so the volume will not increase by deterioration sufficient to require frequent bailing-out and loss of material.

The carburizing rate based on three different activated baths operating at 1650°F. gave the following results:

Temperature, °F.	Time	Case Depth, In.
1650	45 min. to 1 hr.	0.010-0.015
1650	1 hr. to 1½ hr.	0.015-0.018
1650	1½ hr. to 2 hr.	0.018-0.022
1650	2 hr. to 2½ hr.	0.022-0.025
1650	2½ hr. to 3 hr.	0.025-0.027
1650	3 hr. to 3½ hr.	0.027-0.030

The size of the part, the type of furnace used, as well as the weight per furnace load would somewhat affect these figures. Some time is consumed to bring the parts to temperature and heavy charges of work would lower the bath temperature.

Case depth determinations by B. B. Beckwith† at different temperatures are given in Table I and Fig. 1.

Table I
Activated Baths—Case Depths

Temp. Degrees Min- Fahr.	utes	(Inches)									Average
		S.A.E. 1015			S.A.E. 4815			S.A.E. 3115			
		Aver.	Max.	Min.	Aver.	Max.	Min.	Aver.	Max.	Min.	
1500	30	0.0074	0.008	0.006	0.0066	0.007	0.006	0.0072	0.008	0.007	0.0071
1500	60	0.0094	0.001	0.008	0.0092	0.010	0.009	0.0092	0.011	0.008	0.0093
1500	90	0.0118	0.012	0.011	0.0116	0.012	0.011	0.0120	0.013	0.011	0.0118
1550	30	0.0082	0.010	0.007	0.0082	0.009	0.007	0.0077	0.008	0.007	0.0080
1550	60	0.0120	0.014	0.011	0.0120	0.014	0.011	0.0120	0.013	0.011	0.0120
1550	90	0.0152	0.017	0.014	0.0154	0.018	0.014	0.0162	0.018	0.015	0.0156
1600	30	0.0098	0.008	0.011	0.0088	0.011	0.007	0.0092	0.010	0.008	0.0093
1600	60	0.0140	0.015	0.013	0.0142	0.015	0.013	0.0145	0.015	0.014	0.0142
1600	90	0.0185	0.020	0.018	0.0184	0.019	0.017	0.0182	0.019	0.018	0.0184

†B. B. Beckwith, Liquid Bath Carburizing, Trans., A S.M., 1938, v. 26, p. 752.

Cyaniding

By H. B. Northrup*

Caution—Cyanides are violent poisons if allowed to come in contact with scratches or wounds, as for example, on the hands. They are fatally poisonous if taken internally. Fatally poisonous fumes are evolved when cyanides are brought into contact with acids.

Introduction—A hard superficial wearing surface or case can be rapidly and satisfactorily obtained on low carbon steels by subjecting those steels to the cyaniding or case hardening process. When steels are treated by this method they absorb both carbon and nitrogen from the molten salts, so that when they are quenched in water or a suitable oil they develop appreciable hardness in the case.

Due to its greater efficiency and to its lower cost, the use of sodium cyanide in place of the more expensive potassium cyanide is now practically universal. Sodium cyanide for case hardening is used in either of two ways: (1) As a powdered mixture into which the red hot steel is dipped or which is applied to the heated surface of the steel; and (2) as a molten bath into which the steel to be treated is immersed for a sufficient length of time for the reactions to take place.

Properties of Sodium Cyanide—Sodium cyanide is used in the case hardening of steel in four different strengths or grades. Each of these grades, because of its chemical composition, has individual properties as shown in Table I.

Molten sodium cyanide is quite rapidly decomposed when heated above 1580°F. in an open pot. The heavy white fumes which arise from the bath are not especially dangerous, although they are decidedly obnoxious for they irritate the mucous membrane in the nasal passages and thereby induce violent sneezing. This fume when disseminated in the air becomes almost entirely sodium carbonate which, while not dangerous or particularly detrimental to health or property, may become annoying. The escape of fume can be prevented by the installation of a fume-gathering and washing equipment. The suction fan equipment draws the fumes from the pots and passes them through a large washing drum and water spray (mist) before being vented into the outside air. The washers and the spray dissolve the sodium carbonate fume and precipitate any solids carried by the ventilating apparatus.

The chemistry of the decomposition of the bath involves the oxidation of the sodium cyanide to sodium cyanate by the application of heat and exposure to the air (oxygen) as follows:



Continued heating of this sodium cyanate in air (oxygen) forms sodium carbonate, carbon dioxide, and nitrogen as follows:



Table I
Properties of Sodium Cyanide

Grade	Sodium Cyanide, NaCN	Per Cent Sodium Carbonate, Na ₂ CO ₃	Sodium Chloride, NaCl	Melting Point °F.	Sp.gr. at 77°F.	Sp. gr. at 1580°F.	Appearance
96-98 ¹	97	2.3	trace	1040	1.50	1.10	white crystalline solid
75	75.3	3.5	22.2	1094	1.60	1.25	white fused solid
45	45.3	37.0	17.7	1058	1.80	1.40	white fused solid
30	30.0	40.0	30.0	1157	2.09	1.54	white fused solid

¹This grade contains 0.50% sodium cyanate (NaCNO) and 0.20% sodium hydroxide (NaOH). The sodium sulphide (Na₂S) is nil.

Sodium cyanide is a strong reducing agent in the molten state, readily reducing the oxides of most metals. It is deliquescent and gradually decomposes if left in an open container, due to the action of moisture and carbon dioxide. It is soluble in water and the solubility of the anhydrous salt is almost independent of the temperature.

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Steel will heat about four times faster in a molten lead bath than it will in a molten cyanide bath at the same temperature. This is due to the greater heat conductivity of the lead; lead is, therefore, a better production medium than cyanide. However, since slow and uniform heating of steel is advocated to produce most desirable results in any heat treatment, the cyanide method meets with favor because it produces a much milder heat transfer and does away also with special fixtures, necessary in lead hardening for submerging the steel under the surface of the bath.

Uses of Sodium Cyanide

Uses of 96-98% Sodium Cyanide—In the heat treatment of steel, powdered sodium cyanide (96-98% NaCN) is sprinkled upon red hot steel for case hardening; as a "sweetener" to replenish the cyanide content of depleted case carburizing baths; as a bath material for cyanide carburizing direct; and in admixture with potassium cyanide for nitriding steel by the bath immersion method.

Uses of 75% Sodium Cyanide—This mixture is sometimes used as a bath for cyanide carburizing direct, but because of the volatility of the cyanogen (CN) radical, its use in heavy production work is not recommended. It is more frequently used as a replenishing material to raise the cyanide content of depleted baths or to keep them at predetermined cyanide concentrations through regular additions.

Uses of 45% Sodium Cyanide—This mixture is recommended as a suitable bath for the general case carburizing of low carbon and alloy steels. It is very fluid at the operating temperature. The addition of "inerts" (sodium chloride and sodium carbonate) to sodium cyanide tends to retard the decomposition of the sodium cyanide without being detrimental to its case carburizing properties. When this mixture is used continuously in production work, its cyanide strength will of necessity need to be maintained nearly constant through the addition of either the 96-98% or the 75% sodium cyanide.

Uses of 30% Sodium Cyanide—Where the case carburization of low carbon and alloy steels is to be maintained under heavy production conditions, this strength mixture is preferable to any of the preceding. It has the lowest first cost and due to the addition of its inerts, the decomposition of the sodium cyanide of the bath is greatly retarded without being in any manner detrimental to its case carburizing properties.

It is necessary to maintain the strength of the bath constant through the addition of either the 96-98% or the 75% sodium cyanide. It is preferable to use the 96-98% sodium cyanide, because of the absence of inerts in that strength material. The bath is already loaded with sufficient inerts to "fix" the additions of the concentrated material, which should be added in stated amounts at regular intervals. If the cyanogen content of the bath is too low, the bath tends to decarburize and scale the work. "Drag-out" of the bath material is replenished as needed with the 30% sodium cyanide.

The Cyanide Bath—Baths of sodium cyanide are employed in connection with the heat treatment of steel to accomplish two definite purposes as follows: (1) To act as a heating or a reheating medium in connection with the hardening of steels or to prevent surface decarburization and to produce work with a clean surface; and (2) to act as a liquid case carburizing medium affording a quick, efficient, and economical means of obtaining a hard superficial wearing surface.

To accomplish the first purpose, the bath may be either the 30% sodium cyanide, or where a slight case is undesirable that strength material may be diluted with about an equal weight of sodium carbonate. An illustration of the use of the 30% sodium cyanide is the cyanide dip method frequently employed in the heat treatment of automobile transmission and ring gears. An illustration of the use of the diluted material is the heat treatment of tool and stainless steels. To accomplish the second purpose, a bath regulated to maintain a uniform 30% sodium cyanide concentration has been found to meet all the requirements.

Low carbon and alloy steels which are to be cyanided to produce a good wearing surface usually require the surface to be backed up by a fine grained, tough core. This requires the operating temperature of the bath to be in the neighborhood of 1600°F. Case depths and carbon concentrations for three steels are given in Table II. These results show the inefficiency of cyanide as a medium for obtaining deep carbon penetrations. They also show that with even a 1 hr. immersion the carbon concentration is insufficient to account for the extreme hardness obtained

from quenching cyanided steels. Usually immersions run from 30 min. to 1 hr. and produce case depths and carbon concentrations corresponding to those given in the table. Lowering the temperature will correspondingly and proportionately lower the results given in the table.

Since the results obtained in the practice of cyaniding steel are directly proportional to the four variables, time, temperature, mass, and cyanide concentration of the bath, the following data in Tables III, IV and V, all derived from the heat treatment of S.A.E. 1020 steel, show clearly the results of accepted practice involving these variables.

Table II
Case Depths and Carbon Concentrations¹

S.A.E. Steel Nos.	Temp. °F.	Time at Heat, Hr.	Case Depth, In.	Carbon, %
1020	1550	1	0.010	0.62
2315	1550	1	0.012	0.59
3115	1550	1	0.010	0.63
1020	1550	3	0.018	0.74
2315	1550	3	0.018	0.69
3115	1550	3	0.020	0.69
1020	1600	1	0.010	0.50
2315	1600	1	0.010	0.47
3115	1600	1	0.010	0.38
1020	1600	3	0.015	0.65
2315	1600	3	0.016	0.66
3115	1600	3	0.018	0.60

¹Private correspondence.

Test pieces 1 in. dia. x 6 in. long.

Table III
Effect of Temperature on Depth of Case

Temp. °F.	Immersion Time, Min.	Case Depth, In.	Immersion Time, Min.	Case Depth, In.	Immersion Time, Min.	Case Depth, In.
1300	15	0.00025	30	0.00050	45	0.00100
1400	15	0.00135	30	0.00250	45	0.00375
1500	15	0.00175	30	0.00400	45	0.00500
1600	15	0.00320	30	0.00480	45	0.00600

Table IV
Effect of Mass on Depth of Cyanide Case
Cyaniding Temperature 1500°F.

Size of Specimen, Dia., In	Case Depth, In.	
	15 Min. Immersion	30 Min. Immersion
0.25	0.0045	0.0058
0.50	0.0035	0.0042
0.75	0.0030	0.0040
1.00	0.0027	0.0040
2.00	0.0025	0.0040
3.00	0.0023	0.0040

Table V
Influence of Sodium Cyanide Concentration on Case Depth
1 in. rounds, cyanided 30 min. at 1500°F.

NaCN in Bath, %	Case Depth, In.	NaCN in Bath, %	Case Depth, In.
94.3	0.0060	20.8	0.0055
76.0	0.0070	15.1	0.0050
50.8	0.0060	10.8	0.0040
43.0	0.0060	5.2	0.0020
30.2	0.0060		

Within the time range of commercial cyaniding practice, practically no difference in case depth is evidenced by steels of different analysis. The nickel and

nickel-chromium steels, however, tend to give a nicer carbon gradient from case to core than do the carbon steels, but exhibit at the same time, a lower carbon concentration in the case.

The file hardness obtained after water quenching cyanided steel is due to more than the hardening properties imparted to the steel by the added carbon. Since one of the decomposition products of a sodium cyanide bath is nascent nitrogen, it follows that some of this nitrogen has combined with the iron of the steel with the formation of the extremely hard and brittle iron nitride.

Cases obtained by the cyanide process are both hard and wear resisting, although they are not of the high carbon concentration possible with solid commercial carburizing compounds.

Generally, the steels which are case carburized by packing in solid carburizing material or subjected to a carburizing gas can likewise be carburized by cyaniding. They are generally treated by the liquid bath method because of some particular advantage of the process, such as speed of production, the economies of the process, or the peculiar quality of hardness desired in the resultant case.

The cyaniding should in the majority of instances be carried out at a temperature just above the upper critical point of the core, and the steel should be quenched directly from the cyaniding heat. At this temperature the case, which does not approach a tool steel analysis and which has not been held for a sufficient length of time to cause brittleness through excessive grain growth, will quench to the desired hardness and the core will be thoroughly refined and tough.

Quenching of Cyanided Steels—Whether to quench in oil or water depends upon the service requirements the cyanided steels are to meet and the chemical composition of the steel. When water is used it should be as free as possible from dissolved gases, which have a tendency to produce soft spots, so for straight hardness quenching the water should not be air agitated. For maximum hardness and to alleviate warpage, the water should be moving, except where long or thin cyanided parts are to be quenched. It should be normally as cold as possible; variation of quenching water temperature between summer and winter has been known to produce hardness irregularities. Advantage may be taken of the greater hardening capacity of sodium hydroxide solutions or other special aqueous solutions.

For oil quenching a mineral oil should be used. The blended mineral-animal hydrocarbon oils should never be used for the quenching of cyanided steel, because the fatty matter of the animal oil will saponify with the decomposition product of the cyanide bath (alkali) causing the formation of a hard soap. This soap will not only retard the quenching speed of the oil, but may also clog the drains.

Hardness of Cyanided Steels—The usual requirement for the hardness of cyanided steel for shop production is "file hard". While this hardness value is subject to many ramifications, it is still the criterion for shop hardness testing. The Rockwell "C" impression and the scleroscope are also used for testing cyanide hardened surfaces.

The depth of the cyanided zone is best determined by means of the microscope. The cyanided case is composed of two fields which are distinct in character, a martensitic outer zone and a troostite-sorbite inner zone of lower carbon content. The case depth is usually determined by measuring the distance from the outer edge of the specimen to the center of the second zone.

Steels which are cyanided and which do not contain more than 0.65% carbon in the case cannot attribute their hardening power alone to their carbon content. Since one of the decomposition products of the cyanide bath is nitrogen, iron nitride is formed which is an extremely hard and brittle product. At the lower cyaniding temperatures (about 1425°F.) a considerable amount of iron nitride is observed in the form of nitride needles and patches. When the temperatures are in the neighborhood of 1550°F. few of the nitrides are observed, but it is generally accepted that this iron nitride in undistinguishable form produces the hardness otherwise unattainable from the carbon additions.

While the nitrogen absorption affects the hardness of the case, through the formation of iron nitrides, the core is not affected. Steel of the proper grade which has been cyanided above the critical range of the core and quenched into water will snap readily when subjected to stress. When the case is removed by grinding, it is found that the core possesses ductility. Therefore, the brittleness of the core is only apparent. The mechanism for the apparent brittleness may be

due largely to a notch effect in the core after a crack has been formed in the hard case.

Pot Life—The life of cyanide pots in fuel fired furnaces is, in general, an inverse function of the temperature of the combustion chamber. The higher the combustion chamber temperature, the lower will be the pot life. It has been reported¹ that where furnaces were changed from hand-operated to automatic control, the average life of cast steel pots was increased as much as 70%.

Cyanide Containers

Cast Iron Containers—Cast iron fails prematurely and rapidly due to growth. The free graphite of the cast iron grows when subjected to cyaniding temperatures for a considerable length of time, and causes distortion or cracking.

Pressed Steel Containers—Pressed steel containers are probably the most universally used and under proper furnace conditions give high economy. They are highly resistant to the action of molten cyanide, they are homogeneous throughout; and their cost is moderate and commensurate with the increased life of the container.

Cast Steel Containers—Cast steel containers also have a wide application and when of the proper composition and properly cast so as to be free from casting defects give satisfactory service.

Cast Alloy Containers—Nickel-chromium alloy containers have been developed which will give several hundred furnace hours. As a rule, the failure of the cast alloy containers is due to faulty foundry practice. When they are properly cast their higher cost is offset by their increased performance.

Cyanide Containers and Furnaces—The life of any container is shortened by the improper application of heat. As a rule, even physically sound containers will fall from this cause before they will fail from the corroding action of the molten cyanides which they contain. Fuel fired furnaces should, without exception, have their heat application at the top of the pot with the furnace vented at the bottom. In addition to this, with oil fired furnaces, the combustion chamber should be located adjacent to but outside the heating chamber. Such a change from the underfired principle has been known to increase the life of pressed steel pots over 200%. Insofar as pot life is concerned, electric heat applied to the outside of the pot excels all other methods of heat application.

It may be safely stated that the life of any container is in direct proportion to the effectiveness with which the pot is sealed to prevent cyanide from entering the heating chamber. Some furnaces and pots are so designed that it is practically impossible for the molten cyanide to creep into the combustion chamber. In furnaces which do not have specially designed seals, a most satisfactory seal against molten cyanide is obtained by placing a ring of dry powdered fire clay under the pot flange just before dropping the pot in place upon the furnace top.

Quite recently an electric furnace adaptable to cyanide hardening has been introduced and has proved very successful. The furnace operates on alternating current and consists of a well insulated cyanide container into which electrodes are placed which are immersed in the bath. The patented arrangement of the electrodes in the bath utilizes the electromagnetic forces in such a manner as to induce an automatic stirring action throughout the entire pot, tending to produce maximum uniformity of temperature distribution throughout the bath. The heat is generated directly by the resistance of the cyanide bath to the passage of the current. Claims for this improved equipment for the cyanide hardening room include: improved economy of operation; increased production; uniformity of bath temperature; improved uniformity of product; and improved working conditions.

¹Private correspondence.

Selective Carburization of Steels*

Introduction—Selective carburization is carried out for certain special purposes where it is desired to retain soft surface portions after hardening to permit machining, polishing, straightening, or to increase toughness of the piece.

Selective carburization may be accomplished in many ways, but only the principal methods will be considered here. In practice, it is more difficult to secure selective carburizing with gas carburizing than in compound.

1. **Excess Stock at the Surface Portion Desired Soft**—When machining the work, excess stock is left at portions desired soft. After the carburizing operation the piece is pot cooled. The excess stock is then machined off to below the case. The piece will then have a soft surface area following the hardening treatment. This is not properly selective carburizing, but for certain types of tool work, or where but few pieces are to be treated it is an excellent method of accomplishing results. Where threads or sharp corners are to be left soft, this method is, perhaps, the most reliable.

2. **Sand Packing**—The work is packed in sand, exposing only the desired portions to the carburizing compound. The line between the hard and soft portions will not be sharp, as the gas from the compound penetrates the sand to a slight depth. It cannot be used with compounds which have a high shrinkage, as the sand will be displaced, causing hard and soft spots at the protected points. The sand used should be fairly fine and reasonably free from dirt. It must also be thoroughly dried before packing or caking will occur, exposing surfaces which are to be protected. It is an advantage to have the sand at the bottom of the carburizing container and to subject the container to as little jarring as possible after the pieces have been placed in it.

3. **Covering Parts Desired Soft with Cement**—A satisfactory method for preventing carburization of tapped holes and bores of gears is to plug these parts with a cement composed of finely sifted fire clay mixed with sodium silicate (water glass). The proportions used (approximately 2 parts fire clay; 1 part sodium silicate; and about 1/10 part of water) should be regulated so as to secure a cement which will not crack or shrink excessively upon heating and firing. The addition of sand to the cement will sometimes assist in preventing shrinkage. After carburization the cement may be knocked out of the holes. Although this cement will form glass, it is possible by using care to apply this cement to external surfaces, but for this purpose it is not so satisfactory as other methods for selective carburizing. There are prepared cements on the market for this purpose.

Such parts as bushings, sleeves, and piston pins are often strung on close fitting steel rods which minimizes the case in the bore.

4. **Covering Parts Desired Hard with a Carbonaceous Cement**—Selective carburization is obtained by covering the portions of the article to be carburized with a carbonaceous paste or cement which acts as the carburizing compound. After subjecting the work to the proper temperature, the portions covered with the paste are carburized and the other portions of the article are unaffected. With this method the case will not be sharp, but will gradually slope to the portion of the work desired soft.

5. **Protection with Copper Forms**—Pure copper in the form of tubing, bars, cups, sleeves, and discs, is used to prevent carburization for tapped holes, piston pins and ends of shafts. The copper form is placed on, or in the work, as the case may be, with a clearance of not over $\frac{1}{64}$ in. This method is not completely efficient but markedly decreases both case depth and the carbon content of the case.

6. **Plating by Dipping in Copper Sulphate Solution**—A copper plate may be obtained which will partially prevent carbon penetration by either dipping in a copper sulphate solution, or applying the solution with a brush. The part desired soft is first thoroughly cleaned and then dipped in the solution. The part should

*This article was prepared by a committee appointed by the Hartford Chapter of the A.S.M. The committee was composed of L. A. Lanning, Chief Metallurgist, New Departure Mfg. Co., Bristol, Conn., and Dr. R. W. Woodward, Metallurgist, Underwood Elliott Fisher Co., Hartford, Conn.

not be allowed to remain in the solution longer than 5-10 sec., because with this method a thick plate of copper will fall off. The solution is made as follows:

Water	78%
Copper Sulphate	20%
Sulphuric Acid	2%

This method will prevent carburization for short periods. A dip plate is now on the market which is more satisfactory.

7. Electrodeposited Copper—The most widely used method, where production warrants the expense of installation and operation, is that of copper plating by electrolytic methods. Copper plating is effective with many carburizing compounds. With certain compounds copper does not prevent carbon penetration. Apparently the energizer used in the compound is the determining factor in the utility of copper plating as a preventative, because certain energizers will attack and remove the copper.

There is considerable difficulty in depositing the copper plate in recesses.

Two methods may be employed in using the copper plate method:

1. *Plate the Entire Piece*—The entire piece is plated and then the copper is removed by machining or grinding from the portion which is to be hardened.

2. *Selective Plating*—By the use of suitable protective paints, selective copper plating can be obtained which will leave the parts desired hard free from copper.

The usual method is to use japan. The japan is painted on the proper parts and is then baked, being careful not to use too high a baking temperature, 350-400°F. is about the upper limit. After the baking, the plating may be carried out in the usual manner. A second and, perhaps, more simple method of painting with a suitable lacquer paint successfully protects the parts from the copper plate. Care must be used in the choice of lacquers, as many will strip off during the plating operation. The plate does not form on the covered surfaces. In the carburizing operation the japan or lacquer burns off, permitting the gasses of the carburizing operation to penetrate the areas desired hard.

The copper plating operation is standard in every way. The chief requirement is to produce a fine grained, continuous plate. This is done successfully by means of the cyanide bath process, using a solution of sodium cyanide and copper cyanide. Potassium cyanide may be used, but is much more expensive and does not yield results commensurate with the cost.

A suggested plating bath is as follows:

Water	100 gal.
Copper cyanide	20 lb.
Sodium cyanide	28 lb.
Anhydrous sodium carbonate	12 lb.
Sodium thiosulphate (hypo)	1½ oz.

These salts are dissolved directly in the water. Ordinarily the only additions required are sodium cyanide and brightener (hypo). For control purposes the free sodium cyanide should be kept between 0.75 and 1.25 oz. per gal.

The temperature of the plating bath should be maintained between 75 and 105°F. with corresponding current density range of 5-15 amperes per sq. ft. The lower temperatures produce the finest grain size of the deposited copper but for economic reasons the higher temperatures with accompanying greater current density should be used as far as possible provided adequate protection against carbon penetration is obtained.

Precautions—There are certain precautions which must be observed for successful plating and selective carburizing which are briefly as follows:

1. The work must be thoroughly cleaned before japanning. Any oil or grease under the japan causes the japan to loosen during the baking process, which will cause soft spots by allowing the copper to plate under the japan.

2. Before the plating operation, the work must be chemically clean. This is usually accomplished by means of first dipping in a metal cleaning solution, washing in water, dipping in weak hydrochloric acid, washing in water, dipping in a cyanide solution and again washing. This seems to be an elaborate preparation, but if complete protection is to be assured, it is necessary.

3. Care must also be taken to assure that the bath is of the proper strength to give a solid, continuous plate.

4. If any of the parts to be carburized have white or red lead on them, they should not be carburized with copper plated parts, because this will cause the copper to creep over portions of the work desired hard.

5. The thickness of the copper plate necessary for protection depends on a number of factors, such as the plating method used, time of carburizing, and the carburizing temperature. However, for satisfactory protection with most carburizing work a minimum plate of 0.0003 in. should be maintained.

The above methods for obtaining selective carburizing are successful under certain conditions, and their use depends largely upon local conditions. The details of each method must also be developed according to the conditions in the particular plant involved and the type of work to be carburized.

The data given are to be considered as a guide and assistance in accomplishing the desired results.

Nitriding

By Dr. V. O. Homerberg*

Introduction—The nitrogen case hardening process, which is termed "nitriding," consists in subjecting the machined and preferably heat treated articles to the action of a nitrogenous medium, commonly ammonia gas, under certain conditions whereby surface hardness is imparted to the material without necessitating any further treatment. Wear resistance, retention of hardness at elevated temperature, and resistance to certain types of corrosion are other properties imparted to the steel by nitriding.

Of the elements investigated, Dr. Fry found that aluminum ranked first as to the amount of nitrogen with which it combined as well as the stability of the aluminum nitride formed. This compound showed no loss in nitrogen even when heated at 1830°F. Other elements, which formed nitrides with high nitrogen contents include chromium, vanadium, titanium, tungsten, molybdenum, and manganese.

Nitriding Steels—The compositions of the most commonly used nitriding steels are as follows:

	N 125 (Type H)	N 125N* (Type H with Nickel)	N 135 (Type G)	N 135 Modified*	N 230
Carbon	0.20-0.30	0.20-0.27	0.30-0.40	0.38-0.45	0.25-0.35
Manganese	0.40-0.60	0.40-0.70	0.40-0.60	0.40-0.70	0.40-0.60
Silicon	0.20-0.30		0.20-0.30		0.20-0.30
Aluminum	0.90-1.40	1.10-1.40	0.90-1.40	0.95-1.35	1.00-1.50
Chromium	0.90-1.40	1.00-1.30	1.00-1.40	1.40-1.80	
Molybdenum	0.15-0.25	0.20-0.30	0.15-0.25	0.30-0.45	0.60-1.00
Nickel		3.25-3.75			

*Aircraft specifications.

‡"N" preceding a number indicates nitralloy steels.

Special Steels—The nitriding of steels containing principally combinations of chromium, molybdenum, and vanadium have been studied by several investigators.^{2, 4, 5} The results of Sylvester and Whiteside are given in Table I.

Table I
Nitriding Data for Steels Having High Core Hardness

Steel	C	Mn	Ni	Co	Cr	Mo	W	V	Si	Al
A	0.53	0.34	...	...	3.65	0.51	...	0.74	...	...
B	1.50	...	...	...	12.11	0.94	...	0.94	...	...
C	1.33	0.28	0.55	3.08	13.31	0.81	...	...	...	...
D	0.77	0.24	...	...	3.83	8.63	1.35	1.01	...	...
E	1.20-1.30	...	...	...	1.00-1.25	...	4.75-5.25	0.15-0.25	...	...
F	1.04	...	...	...	1.25	1.33	0.51	0.25	...	...
G	0.37	0.34	0.23	...	4.92	1.32	...	0.44	1.06	...
N 125N	0.25	0.55	3.54	...	1.11	0.30	...	...	...	1.30

	Nitriding Temp., °F.	Nitriding Time, hr.	Vickers Hardness, 10 kg. Load	Depth of Case, in.	Core Hardness, Rockwell C
A	975	72	975	0.018	47
B	1000	48	1150	0.012	59
C	1000	72	970	0.012	50
D	1000	72	1400	0.015	63
E	1000	48	925	0.008	56
F	1000	48	975	0.018	47
G	900	48	1100	0.014	43
N 125N	975	35	1064	0.016	44

Nickel Nitriding Steels—French and Homerberg³ have studied the role of nickel in nitriding steels. Its effects are to strengthen and toughen the case with moderate decrease in case hardness. It strengthens and hardens the core and thereby provides better support to the case. It develops dispersion hardening in steels containing appreciable proportions of aluminum, by means of which articles may automatically acquire higher core strength and elastic properties during nitriding.

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Steel N 125N was oil quenched from 1650°F. followed by tempering at 1200°F. The core properties are as follows:

	Before Nitriding	After Nitriding
Tensile strength, psi.....	132,400	190,250
Yield point, psi.....	114,600	180,000
Elong. in 2 in. %.....	22	15
Reduction area, %.....	59.4	43.4
Brinell hardness no.....	277	415

High Sulphur and Selenium Nitriding Steels—A high sulphur nitriding steel is used for free machining when maximum impact properties are unnecessary. Fig. 1 shows the properties of a steel low in sulphur and one with high sulphur. Selenium is rapidly displacing sulphur for the purpose of promoting machinability.

A typical composition of such a steel is as follows: Carbon 0.30-0.40; manganese 0.50-1.10; silicon 0.30 max.; aluminum 0.75-1.50; chromium 1.00-1.50; molybdenum 0.15-0.25; sulphur 0.06 max.; selenium 0.15-0.25.

Nitriding of Austenitic Steels

—The austenitic steels investigated by Jones¹ were of the nickel, chromium-nickel, chromium-nickel-tungsten, manganese and nickel-manganese types. A temperature of 930-950°F. with a nitriding period of 90 hr. was employed. With some steels, modifications of the usual process were made, such as a variation in the ammonia dissociation, nitriding at a higher pressure, and changing the character of the surface of the steels preceding the nitriding treatment by pickling in acid or by copper plating.

He found that the chromium-nickel austenitic steels did not harden consistently until the

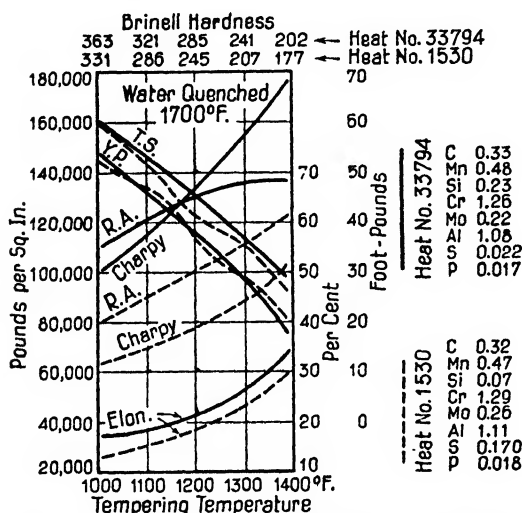


Fig. 1—Physical properties of high and low sulphur nitriding steels.

protective oxide surface film was removed. It was found that the oxide film reformed in local areas on the surface of some of the steels and, after nitriding, showed a dull exterior where the steel had hardened and a shiny area where it had not hardened.

The nitriding alloy most commonly used in this country has the following approximate composition: Carbon 0.45%; nickel 14.0%; chromium 14.0%; tungsten 2.5%; and molybdenum 0.30%. The usual practice is to treat with 50% hydrochloric acid and then nitride at 1000°F. for 50 hr.

Proper Condition of Steel for Nitriding—The nitriding steels do not warp or distort to any appreciable extent provided the internal stresses resulting from machining and heat treating are removed before nitriding. The steel should possess a sorbitic structure prior to case hardening with ammonia gas. The steel is generally purchased in the heat treated condition, unless forgings are to be made.

A sufficient amount of the heat treated stock must be removed to eliminate all traces of decarburization. Also, a reheating to a sufficiently high temperature (generally 1200-1300°F.) should be performed in order to remove stresses that are produced during the rough machining. This reheating is generally applied before the final machining or grinding operation.

A forging temperature of 1950-2200°F. is commonly used. Quenching in a suitable medium followed by tempering at 1150-1350°F. is common practice for producing a sorbitic structure suitable for machining and nitriding. In the case of the annealed forgings, they should be rough machined, then heat treated so as to produce a sorbitic structure, after which the machining or grinding is completed. Enough stock should be left for this final operation to insure the complete removal of the decarburized layer that is produced during the heat treating operation.

Mechanical Properties—The mechanical properties of several of these nitriding steels are given in Table II. Standard specimens (0.505 in. dia. and 2 in. gage length) were used for the tensile tests.

Table II
Physical Properties of N 125, N 135, and N 135 Modified

Tempering Temp., °F.	Yield Point, psi.	Tensile Strength, psi.	Elong. in 2 in., %	Reduction of Area, %	Charpy Impact, ft.-lb.	Brinell Hardness No.
N 125^a						
800	156,300	178,800	12	47	20.6	400
900	143,500	170,000	16	49	25.5	365
1000	133,300	160,000	17	54	30.1	340
1100	117,500	134,500	18	61	48.1	290
1200	103,800	122,000	21.5	67	59.2	255
1300	85,500	102,500	27	72	69.0	228
1400	75,000	90,500	32	73	73.0	190
Annealed	60,000	80,000	34	70.5	47.8	157
N 135^b						
800	180,000	224,500	11	36	12	445
900	165,000	206,300	11.5	37.5	15	415
1000	158,000	182,500	15	50	22	363
1100	137,500	156,000	16.5	57	35.2	330
1200	120,000	138,000	20	60	44.0	285
1300	103,300	121,000	23	62.5	55.3	226
1400	80,500	104,300	28	59	64.5	200
Annealed at 1450	69,000	95,000	30	67.5	31.6	186
N 135 Modified^c						
					Rockwell C Hardness	
1000	160,000	185,000	12.5	42.0	40	375
1100	133,000	157,000	16.5	50.5	33-34	321
1200	115,000	132,500	19.5	56.5	27-28	286
1300	84,000	109,000	25.5	60.0	20	228

^aN 125—C 0.23, Mn 0.51, Si 0.20, Cr 1.58, Al 1.24, Mo 0.20, P 0.011, S 0.011. Quenched in oil from 1750°F. Held at temperature 30 minutes.

^bN 135—C 0.36, Mn 0.51, Si 0.27, Cr 1.49, Al 1.23, Mo 0.18, S 0.010, P 0.013. Quenched in oil from 1650°F.

^cN 135 Modified—Quenched in oil from 1700°F.

Effect of Size on Mechanical Properties—The properties will vary with larger sections. Sergeson and Clark¹ recommend water quenching from 1700-1750°F. for steels N 125 and N 135. Their results, showing the effect of size on properties, are given in Table III. These values represent results of tests taken longitudinally as near halfway center to edge as possible.

Table III
Effect of Size on Mechanical Properties of N 125 and N 135^a

Tempering Temp., °F.	Tempering Time, hr.	Size of Round Section, in.	Yield Point, psi.	Tensile Strength, psi.	Elong. in 2 in., %	Reduction of Area, %	Brinell Hardness No.
N 125 — Composition: C 0.26, Mn 0.50, Si 0.13, Cr 1.04, Mo 0.21, Al 0.95.							
1000	4	4	102,300	117,900	19.5	54.7	277
1100	4	4	93,900	110,000	19.5	58.5	228
1200	4	4	82,800	103,900	20.0	61.0	217
1000	3	3	103,900	119,800	18.0	54.7	269
1100	3	3	96,800	114,800	18.0	57.3	255
1200	3	3	83,500	104,300	21.0	61.0	223
1000	2	2	124,900	141,900	14.5	49.2	302
1100	2	2	104,900	121,300	18.0	59.8	262
1200	2	2	94,900	112,000	19.0	63.6	228
1000	1	1	130,900	146,300	14.0	53.3	332
1100	1	1	112,300	126,800	15.5	58.5	293
1200	1	1	104,900	122,300	18.0	64.8	255
N 135 — Composition: C 0.35, Mn 0.60, Si 0.22, Cr 1.30, Mo 0.25, Al 0.94.							
1000	4	4	134,800	155,900	13.0	40.8	340
1100	4	4	113,300	132,800	16.5	47.8	302
1200	4	4	100,500	124,900	18.0	51.9	269
1000	3	3	140,500	158,800	13.0	40.4	340
1100	3	3	120,500	140,000	15.5	47.8	293
1200	3	3	104,900	126,900	17.5	56.0	255
1000	2	2	149,800	171,300	12.5	40.4	340
1100	2	2	137,900	156,300	15.5	50.6	302
1200	2	2	135,000	154,900	15.5	49.2	269
1000	1	1	164,800	182,300	12.5	44.4	351
1100	1	1	138,900	156,000	15.0	51.9	302
1200	1	1	120,900	139,300	20.0	58.5	269

^aBars for both steels were water quenched from 1725°F.

The Nitriding Process—The nitriding process consists in subjecting the articles to the action of ammonia gas at temperatures ranging from 930-1200°F. Various nitriding cycles have been recommended by several investigators,^{9, 10, 11, 12, 13} but the range most commonly used is 950-1000°F.

Nitriding Equipment—Electric, gas, and oil fired furnaces are suitable and must maintain uniform temperature in the nitriding container. Special nitriding furnaces have been described by Roth,¹⁴ Lapelle,¹⁵ and Cowan.¹⁶

A batch type furnace and the nitriding equipment used are shown in Fig. 2.

Ammonia Gas—

The tank of ammonia must be placed in such a position that the bent tube inside the tank has its open end in the gaseous atmosphere and does not dip into the liquid ammonia. The use of a suitable needle valve insures the control of a steady and even flow of gas.

Although anhydrous ammonia is a commercial product, the final traces of water, if present, can be removed by passing the gas through a tower containing lime. The inlet and the outlet tubes are made of nickel and the articles in the box are supported preferably on nickel or nickel alloy screens. The inlet tube extends along the bottom of the box to the back while the outlet tube is at the front and near the top of the box. Pyrometers are inserted into both the container and the furnace. The gas mixture from the container passes through a wash bottle to indicate the back pressure, which should be about 1-2 in., as well as the rate of flow of the gas, and finally passes into the atmosphere or is washed into the drain in the sink by means of a suitable baffle.

Ammonia gas decomposes to a certain extent into nitrogen and hydrogen according to the following reaction: $2\text{NH}_3 \rightleftharpoons 2\text{N} + 3\text{H}_2$. Nitrogen, which is very active at the moment of the decomposition of the gas, combines to a certain extent with the alloying elements in the steel to form nitrides. These nitrides, which are in a fine state of dispersion in the case, impart extreme hardness to the surface of the steel, a hardness which gradually decreases inwardly until it corresponds to that of the core.

The gas mixture leaving the furnace consists of hydrogen, nitrogen, and undissociated ammonia. The ammonia gas is soluble in water whereas the hydrogen and the nitrogen are insoluble. Advantage is taken of this fact in the determination of the extent of the ammonia dissociation during the nitriding operation. The special pipette shown in Fig. 3 is used for making this determination. The dissociation is generally maintained at approximately 30%.

At the time that a determination of the extent of the ammonia dissociation is to be made, the stopcocks at "C" and "E" are closed while "D" is open and the stopcock at "A" is turned so as to admit the gas mixture from the container into the graduated chamber. After the air has been expelled, stopcock "D" is closed and "A" is turned so as to by-pass the gas mixture. Reservoir "G" is filled with water, after which the stopcock "E" is opened to admit the water into the graduated chamber. The water immediately hydrogen and nitrogen. The water solution should reach approximately the 30 cc. absorbs the ammonia and the atmosphere above this solution contains the insoluble

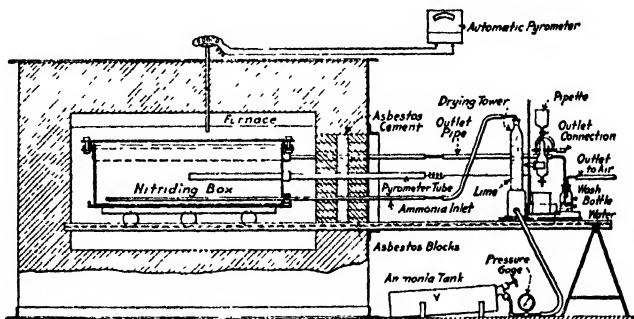


Fig. 2.—Nitriding furnace and equipment.

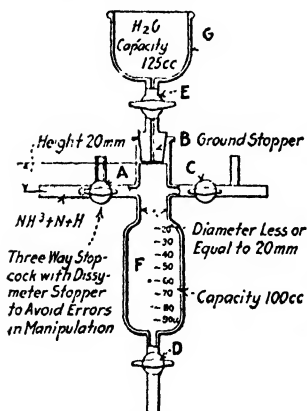


Fig. 3.—Pipette for determining ammonia dissociation.

mark, indicating 30% of dissociation. If it is much above this value the flow should be increased, while if much below the degree of dissociation can be increased by decreasing the flow of the gas by means of the needle valve.

Nitriding Containers—Unfortunately, low carbon steel absorbs nitrogen and the inside surface of containers becomes embrittled. Besides the embrittlement, it is also believed that the nitrided surface has a harmful influence in catalyzing the ammonia in contact with it and thereby preventing the proper nitriding of the articles. It is the atomic nitrogen in immediate contact with the steel parts that is responsible for the nitriding.

Enameled low carbon steel containers have been used successfully. Such a coating is easily chipped and may spall at the nitriding temperature because of the pressure of the gases within the steel. Careful handling of the articles to be nitrided must be exercised in order not to chip or crack the enamel.

High chromium and high nickel alloy containers (welded) are being used successfully with the approximate compositions: Chromium 12%; nickel 80%, or chromium 25%; nickel 20%.

Methods of Sealing Containers—Various sealing methods have been discussed by Sergeson¹¹ and Deal as shown in Fig. 4.

Depth Hardness Data—Typical depth hardness curves for several nitriding steels are shown in Fig. 5a and 5b.

The hardness testing machines that are most commonly used for testing the hardness of nitrided steels are the Rockwell Superficial hardness tester and the Vickers.

Growth on Nitriding—Articles increase slightly in size after nitriding. This growth is dependent mainly on the temperature and the time of nitriding. Absence of decarburization is of vital importance as the

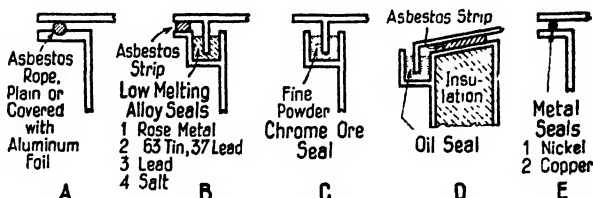


Fig. 4—Methods of sealing containers.

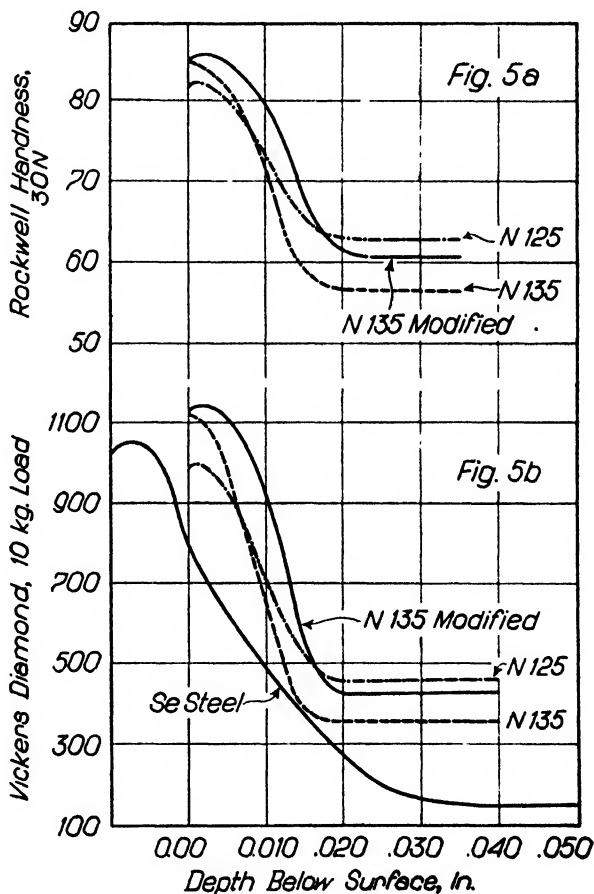


Fig. 5a—Depth-hardness curves. All steels were quenched in water from 1725°F. and tempered at 1000°F. nitrided at 975°F. for 48 hr.

Fig. 5b—Depth-hardness curves for same steels and treatments as Fig. 5a, but in addition a depth-hardness curve for selenium nitriding steel C 0.34%, Cr 1.36%, S 0.033%, Al 1.13%, Mo 0.22%, Se 0.28%. Nitrided at 975°F. for 48 hr.

nitriding of a decarburized surface not only produces excessive growth but also produces a brittle case. The amount of growth is constant under the same conditions, so that after it has once been determined for a given material it can be allowed for in the final machining, grinding, or lapping. An increase in diameter of 0.002 in. in a specimen having a case depth of 0.030 in. is a fair example of this growth. Cunningham and Ashbury¹¹ found that the growth on a 1 in. dia. solid bar that had been nitrided for 80 hr. at 930-940°F. varied from 0.0012-0.0014 in. A bar of the same dia. but bored with a $\frac{1}{2}$ in. dia. hole expanded the same extent on the outside dia., but was reduced to the extent of 0.001 in. on the inside dia. A third bar bored with a $\frac{3}{8}$ in. dia. hole, leaving only $\frac{1}{8}$ in. wall, expanded approximately 0.005 in. on the outside dia. and 0.0012 in. on the internal diameter. This variation of internal growth is apparently controlled by the thickness of the surrounding metal. Undoubtedly, the tendency of the bore to expand increases as the thickness of the wall diminishes.

Hubbard and Robinson determined the change in dimensions of hollow cylinders with varying wall thickness. The outside dia. of the specimens was 2½ in. with wall thicknesses of $\frac{1}{8}$, $\frac{1}{4}$ and up to 1¼ in. at $\frac{1}{8}$ in. intervals.

The specimens were rough machined after quenching from 1725°F. followed by tempering at 1300°F. for three hours. After leaving $\frac{1}{8}$ in. for final grinding, the hollow cylinders were heated to 1000°F. for 3 hr. to relieve stresses and then ground to final dimensions. The specimens were nitrided at 975°F. for 72 hr. The results of this investigation are shown in Fig. 6.

Walsted¹² states* that the growth of the diameter of a solid cylinder on nitriding is undoubtedly dependent on case depth and will be the same whatever the original diameter of the cylinder. Homberg and Walsted¹³ have called attention to the "corner effect" that occurs on nitrided parts possessing sharp corners. The growth on all surfaces combines at the corners to form projections containing a high nitrogen content with no supporting core. This portion of the case is brittle and likely to chip. Such a condition should be avoided by providing rounded corners.

Protection Against Nitriding—The most efficacious protective agent against nitriding is tin or a solder containing 80 parts of lead and 20 parts of tin. Although tin and the alloy of lead and tin melt at a lower temperature than that used in nitriding, ample protection is provided by the thin layer that is held to the article by surface tension. Too much of the protective agent may cause the excess amount to drop onto articles at points where protection is not desired. A liquid flux is used which is made by adding zinc to a solution containing 500 cc. hydrochloric acid, 250 cc. water and 15 g. of ammonium chloride until no further action takes place. Parts to be tinned should be entirely free from rust or scale.

For protection of the end of a part, clean the part to be protected, apply flux and dip into molten tin or solder to the depth to be protected. Remove excess tin or solder with wire brush. For protection of the mid-section of a part, protect ends to be hardened with fireproof varnish (such as Bakelite varnish), apply flux and dip piece into molten metal to required depth. Remove varnish and excess metal with wire brush. For protection of small surface or keyways, apply flux to area, then apply protective agent with a soldering iron.

Tin plating is an excellent means for providing protection. A plating of 0.0007 in. will protect the parts and will not run. Nickel plating also gives satisfactory results. A thickness of 0.0005 is sufficient.

Painting with either a mixture of glycerine and tin oxide or shellac and pure tin oxide is also used although complete protection is not always obtained with

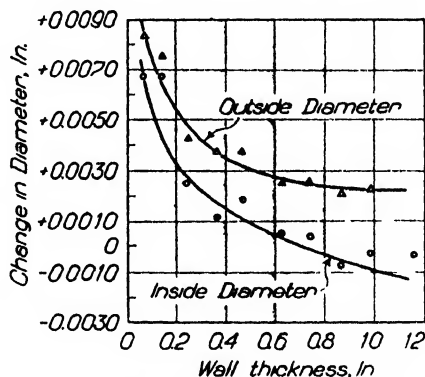


Fig. 6—Growth in rings or cylinders of N 135 due to nitriding.

*This statement is true only if the general structure of the part is the same. A large forging, in which it is difficult to obtain a fine grained sorbitic structure, will show a greater growth than a small part in which the structure is uniformly fine grained sorbite.

these materials. A paste containing lead and tin in a fine condition in a suitable vehicle is also used. Powdered tin in clear Feroleum provides a satisfactory paint.

Distortion—Parts of uniform section and parts which have been treated so that no machining stresses are present, can be nitrided without appreciable distortion. The removal of the stresses produced by rough machining is accomplished by reheating to 1100-1200°F. before final machining or grinding. Usually a period of 1-4 hr. at temperature is sufficient. Slight distortion may occur in other sections because of unequal growth.¹³

Thin strips, after protecting one of the sides against nitriding, bow with the nitrided part on the convex side. The extent of the bowing increases as the time of nitriding is lengthened.

Slightly distorted parts can be straightened both cold and hot, but the latter is preferred. Such straightening, especially when it is done cold, should be performed with caution in order not to crack the case. Any cracks that may be produced will lead to fatigue failures and also cause failure to withstand corrosion. Since no softening of the case takes place on heating at 1200°F. for a short time, it is entirely safe to heat to this temperature for straightening.

The complete removal of internal stresses before nitriding and the proper placing of the parts in the nitriding container will greatly remove the possibility of warping or distortion.

Surface Defects—If the decarburized surface is not all removed before nitriding, the case will spall. Parts that are coated with rolling or forging scale necessitate the removal of $\frac{1}{32}$ - $\frac{1}{16}$ in. of material to thoroughly eliminate the decarburized layer.

Softening and Denitriding—As there are occasions when it is desirable to soften nitrided parts for the purpose of making changes in design, it is frequently desirable to soften the nitride case. Merten¹⁴ recommends the heating of the nitrided parts in a fused bath consisting of a mixture of 50% each of sodium and potassium chlorides at a temperature of 1500°F. whereby a decomposition of the nitrides takes place. Sergeson and Deal¹⁵ state that softening can be performed by annealing at 1800°F. but that renitriding to obtain the original hardness cannot be achieved. Cunningham and Ashbury¹⁶ state that decarburization accompanies denitriding and that the original hardness is not obtainable on renitriding. The complete removal of the softened layer is necessary before the renitriding can be performed with success. Such a procedure obviously precludes the use of these softening processes on finished articles.

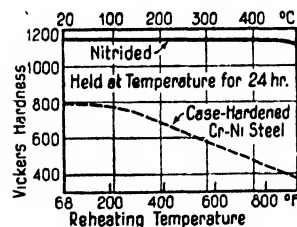


Fig 7—Hardness comparison of nitrided and carburized cases at room and elevated temperatures.

Retention of Hardness on Nitride Case—The retention of hardness of the nitride case and the softening of the case of a case hardened chromium-nickel steel are shown in Fig. 7.

Tensile Properties of Nitrided Steels—Since the nitride case represents only a small portion of the cross section of a tensile test piece, it has little effect on the tensile strength. Table IV shows the results of tests conducted by Homerberg and Walsted.²² Tensile specimens were quenched in oil from 1650°F., and tempered as shown.

Table IV
Mechanical Properties of Steel N 135, Nitrided*

Tempering Temp. °F.	Condition Tested	Tensile Strength, psi.	Yield Point, psi.	Elong. in 2 in., %	Reduction of Area, %	Charpy Impact, ft.-lb.
1000	Tempered	182,000	165,000	15	50	22
1000	Nitrided	171,000	139,000	6	13	14
1100	Tempered	156,000	138,000	18	57	35
1100	Nitrided	159,000	129,000	5	16	18
1200	Tempered	138,000	120,000	20	60	44
1200	Nitrided	138,000	110,000	4	17	21
1300	Tempered	121,000	103,000	23	62	55
1300	Nitrided	123,000	98,000	8	20	24

*Tensile specimens were nitrided 90 hr. at 900°F.

Coefficient of Linear Expansion—The Ludlum Steel Co. reports the following data for the coefficient of linear expansion for steel N 135, and the Firth-Brown Research Laboratory, the coefficient of expansion for the case.

Temp. °C.	Centimeters per °C.		Temp. °C.	Case	cm. per °C.
	Unnitrided	Nitrided			
0-100	0.00001184	0.00001214	20-100		0.0000107
0-200	0.00001188	0.00001218	20-200		0.0000113
0-300	0.00001192	0.00001222	20-300		0.0000118
0-400	0.00001196	0.00001226	20-400		0.0000123
0-500	0.0000120	0.0000123	20-500		0.0000129

The coefficient of linear expansion for a 0.25% carbon steel from 0-200°C. is 0.0000115 cm. per °C.

Fatigue Properties of Nitrided Steels—Since nitrided steels are frequently used in applications where they are subjected to repeated stress, the effect of nitriding on the endurance properties is of considerable importance. Nitriding increases the endurance range as determined by reversed bending.

Sutton has summarized the results of rotating beam fatigue tests that were performed by a number of investigators. They are given in Table V.

In fatigue tests conducted by Sutton, an examination of the fractures of Wöhler test pieces indicated that the cracks commenced at a point near the junction of the case and the core but within the core material. His results indicate that the fatigue fracture of a nitrided specimen results when the stress exceeds the fatigue limit of the core at a point near the junction of the case and the core. Ordinarily, the permissible loads on nitrided specimens are therefore limited by the fatigue properties of the core material.

Table V
Summary of Results of Rotating Beam Fatigue Tests

[illegible]

The effect of scratches and notches was studied by Hengstenberg and Malländer. Since fatigue cracks in nitrided parts do not commence at the surface, small surface defects (notches, threads and scratches) are not so highly important as in other steels. Hengstenberg⁷ and Malländer notched a nitrided specimen to a depth of .0004 in. by grinding. In a rotating beam type of fatigue test this specimen remained unbroken after being subjected to test at a stress range of 71,700 psi., but failed at 88,500 at an undamaged place, the origin of the fracture lying in the

core. Further experiments showed that a turned notch .0004 in. deep that was cut before nitriding had no effect on the fatigue strength while the same notch on an unnitrided specimen reduced the fatigue strength by 45%.

The results of fatigue tests on a nitrided and unnitrided steel with different types of surfaces are given in Table VI.

Johnson and Oberg²³ found that the V notches in the case did not reduce the fatigue limit provided that the notches were cut before nitriding. They also found that scratches were without effect until their depth was about 70% of the depth of the case.

Table VI
Results of Surface Condition Fatigue Tests

Condition	Tensile Strength, psi.	Fatigue Strength, psi. (Rotating Beam)		
		Polished Smooth	Sharply Notched ^a	Fillet ^b 0.04 in.
Not nitrided	138,900	73,900	40,300-41,400	45,900-47,000
Nitrided for 60 hr. ....	.....	87,400-88,500	87,400-88,500 ^c	87,400-88,500

^a0.004 in. deep, as sharp as possible; notched before nitriding.
^bAt the joint of test length (0.30 in. dia.) to ends (0.48 in. dia.). Samples finish machined before nitriding.
^cSpecimens did not break at notch.

Fuller²⁴ showed that the high endurance value for nitrided steels at elevated temperatures could be expected to be retained up to 800-1000°F. because the hardness and strength values of the case are not materially affected at these temperatures, (see references 1, 26, 27, and 28).

McAdam²⁵ tested a steel containing 0.36% carbon, 2.03% aluminum, and 1.62% chromium. It was oil quenched from 1750°F. and tempered at 1200°F. All the grinding and polishing were done prior to the nitriding. The resistance to fatigue corrosion of this steel was superior to stainless, chromium-nickel, and chromium-vanadium steels, when tested in carbonated and salt waters.

Tensile Properties at Elevated Temperatures—Homerberg and Walsted²⁶ oil quenched a nitriding steel from 1650°F., tempered at 1000°F. and then nitrided 90 hr. at 900°F. The results obtained at high temperatures are given in Table VII.

Table VII
Effect of Temperature on Properties of Nitrided N 135

Testing Temp. °F.	Tensile Strength, psi.	Elongation in 2 in., %	Reduction of Area, %
800	134,000	6.5	30.5
900	124,000	9.5	31.0
1000	98,000	15.5	44.5
1100	42,000		
1200	39,000		
1300	28,000		
1400	20,000		

Creep Tests on Nitrided Steel—Malcolm²⁷ tested nitrided steel at 1000°F. under a load of 10,180 psi. After 4,000 hr. the extension amounted to 0.002 in. per in. with no further extension during an additional 5,000 hr.

Abrasion and Wear Resistance of Nitrided Steels—Malcolm²⁷ tested nitrided and stainless steels in a wear testing machine under a pressure of 200 lb. The nitrided steel withstood 100,000 strokes without scoring and with no appreciable wear, whereas the stainless steel was badly abraded after 1,000 strokes.

Homerberg and Walsted²⁶ have reported the results of wear tests in which nitrided steel was tested against itself and against a number of other materials without lubrication. The two materials that showed excellent results when operated against nitrided steel were the nitrided steel itself and a bronze of the following composition: Copper 80.2; tin 11.5; nickel 5.5; and zinc 2.8%.

Leaded and graphitic bronzes are generally used as bushings to run against nitrided steels. A bronze containing 80 copper, 10 tin and 10 lead is suitable for the purpose.

Corrosion Resistance of Nitrided Steel—Sergeson and Deal¹¹ have reported the corrosion resisting properties of nitriding steels after nitriding for 90 hr. at 975°F. Their conclusions are as follows:

1. Nitrided steel is not adapted for use in mineral acids, such as sulphuric and hydrochloric.
2. Nitrided steel is extremely resistant to alkali, atmosphere, crude oil, natural gas combustion products, tap water, and still salt water.
3. It is slightly attacked in aerated salt water and under alternate wetting with salt water and drying.

Malcolm¹² has reported that nitrided steel shows excellent resistance to oxidation and corrosion under the action of superheated steam.

It should be clearly emphasized that the maximum resistance to corrosion is shown by the outermost layer of the nitrided case. Therefore, it is of importance that nitrided specimens should not be ground after the nitriding operation if maximum resistance to corrosion is desired.

Welding of the Nitriding Steels—Homerberg¹³ and Walsted have welded nitrided steels by the atomic hydrogen process and by flash welding. A welding rod of the same material was used in the atomic hydrogen process. No appreciable difference between hardness at the weld and away from it was shown after nitriding.

Determination of Case Toughness of Nitrided Steel—The character of the impression produced by the various hardness testing machines is indicative of the toughness of the case. If the impression is free from spalled edges the nitride case will be tougher than one in which the edges are not well defined.²

Precautions and Recommendations

1. To insure the best nitriding results, the steel should be heat treated so as to possess a uniformly sorbitic structure.
2. Before nitriding the steel must be free from decarburization.
3. If freedom from distortion is of paramount importance, the internal stresses produced by machining or heat treating should be removed before nitriding by heating to a temperature of 1000-1300°F.
4. Since some growth takes place on nitriding, this should either be allowed for in the final machining or grinding operation prior to nitriding or removed by lapping or by careful grinding. However, the removal of only a slight amount of the nitride case is permissible.
5. If maximum resistance to corrosion is desired, the parts should be used as they come from the nitriding container.
6. Nitrided steels of the nitralloy type should not be used where resistance to the corrosion of mineral acids is encountered or where resistance to sharp abrasive particles at high velocities is required, as in sand nozzles.
7. If straightening is required after nitriding, it should be done hot at 1200°F., although some straightening may be done cold.
8. If maximum hardness and maximum resistance to impact are desired and the question of maximum corrosion resistance is not of vital importance, the removal of 0.001-0.002 inch of the nitrided case is desirable. The amount to be removed depends upon the original case depth. This operation will remove the more brittle and somewhat softer surface layer.
9. If nitrided articles exhibit a shiny gray surface after their removal from the container, the results should be viewed with suspicion. Invariably, the case will be shallow and below normal hardness. The articles should have a matte gray appearance, although a slight discoloration does not indicate faulty nitriding. A slight vacuum may be created within the container when the furnace is shut off and if a small amount of air enters through the gasket, the articles may show various hues such as pink, blue, or light brown. Increasing the flow of ammonia at this stage or nitriding in the presence of copper turnings will frequently prevent this discoloration. The opening of the container at too high a temperature will also cause surface discoloration.
10. Specimens that can be checked for hardness and depth of case should be included with every charge.
11. Applications requiring a high core hardness to support the case when high compressive stresses are present require nitriding steels of special analyses.
12. Although special nitriding furnaces are desirable, such equipment is not absolutely necessary. In most instances these special furnaces are constructed so that they can be used for general heat treating purposes when not used for nitriding. The most essential point is that a furnace must maintain a uniform temperature within the nitriding container.

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Aluminum Impregnation

(Calorizing)

By B. J. Sayles*

Definition—Calorizing is a trade name for an aluminizing process for alloying the surface of carbon or alloy steel with aluminum by diffusion. The depth to which the action penetrates varies from 0.005-0.040 in., but on thin articles the usual depth is 0.025-0.030 in., the surface layer of iron-aluminum alloy, usually containing approximately 25% aluminum.

Methods—There are several distinct processes for performing the aluminizing operation as follows:

Old Style Powder Calorizing—This practice was in general commercial use until 1935. The articles were hermetically sealed in revolving retorts packed in a powder compound in which the active ingredient was powdered aluminum. Time of treatment was usually four to six hours at a temperature of 1550-1700°F. The resulting iron-aluminum surface alloy was of a depth of 0.001-0.006 in. and contained about 60% aluminum.

The surface alloy possessed excellent heat enduring and sulphur corrosion resisting qualities but, by reason of the high aluminum content, was brittle and inclined to spall from the surface whenever the article was subjected to mechanical abuse such as the application of a rotary tube cleaner.

Modern Powder Calorizing—Since 1935 this process† has continued with the foregoing method for securing a primary iron-aluminum alloy, but subsequently the work is removed from the rotating retort and heat treated for periods of 12-48 hours at temperatures from 1500-1800°F. to cause the aluminum to penetrate by diffusion to depths ranging from 0.025-0.040 in. Since no compound is in contact with the work during the heat treatment, the aluminum content at the surface of the article is reduced to 25% or less. This is ample for heat enduring and corrosion resisting purposes. With this aluminum content the surface alloy obtains the qualities of toughness and ductility not to be found in the older process.

Pack Calorizing—This consists of packing the work in hermetically sealed stationary boxes with the powdered aluminum compound. The process requires from 6-24 hr. at temperatures ranging from 1500-1800°F. Since it is a combined aluminizing and diffusion heat treatment, no further treatment is needed when the work is removed from the container. The process is of particular value for handling articles of light gage or irregular shape which might be damaged by processing in rotating retorts.

Dip Calorizing—The work, suitably cleaned and fluxed, is immersed in molten aluminum in a manner similar to that employed for hot dip galvanizing. This results in a superimposed coat of practically pure aluminum with slight formation of an iron-aluminum alloy at the face of the parent metal. Under suitable conditions the thickness of this alloy layer may be increased by subjecting the material to heat treatment, though a primary coat of pure aluminum can not be diffused to give surface alloys of relatively low aluminum content.

The process is of particular value where the corrosion resistance of pure aluminum is desired combined with the strength of the underlying steel.

Flank Process—This is essentially a dip Calorizing process for wire but is distinguished by maintaining the steel to be treated in hydrogen atmosphere after it leaves the pickle bath and before immersion in the molten aluminum bath.

While wire readily lends itself to the passage through a hydrogen tunnel between the pickle and aluminum baths, the process may be impractical when handling a wide range of various sizes and shapes.

Martin Process—In this process the surface alloy of iron-aluminum is formed by treating the metal in aluminum chloride vapor at high temperature. It is reported that the surface alloy thus obtained is shallow compared to the other processes.

*Calorizing Co., Pittsburgh, Pa. Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

†U. S. Patent No. 1,988,217.

Spray Gun Process—For a description of the process for spraying molten aluminum see page 1115.

Oxidation Resistance—Calorizing protects steel from oxidation and flue gas corrosion at high temperature by the formation of a film of aluminum oxide on the surface. This film is self-replacing as long as any appreciable amount of aluminum remains at the surface. At temperatures under 1400°F., the life of a Calorized part is a matter of years. Calorized parts, however, are used up to temperatures of 1700°F. for purposes where the life of the part, such as a heat treating pot, is usually long enough to justify the higher cost as compared to that of carbon steel.

Table I gives the relative oxidation resistance of some steels before and after calorizing.

Table I
Oxidation Test

Type of Material	1000 hr. at 1100°F.		1000 hr. at 1200°F.	
	Not Calorized	Calorized	Not Calorized	Calorized
	Weight Increase, Milligrams per Sq. Cm.			
C .08-.20, Cr 18, Ni 8.....	....	...	1.1	0.6
C .08-.18, Mn 0.30-0.60, Cr 5, W 1.....	....	...	17.5	1.0
C .08-.18, Mn 0.30-0.60, Cr 5, Mo 0.50.....	16.6	...	36.6	0.8
C .08-.18, Mn 0.30-0.60, Cr 5.....	....	...	39.5	0.6
C .08-.18, Mn 0.30-0.60, Mo 1.....	35.3	...	83.6	1.0
C .08-.18, Mn 0.30-0.60, Mo 1.50.....	35.4	1.3	....	....
C .08-.18, Mn 0.30-0.60, Cr 2.00, Mo 0.50.....	21.4	....	....	....
C .08-.18, Mn 0.30-0.60, Cr 1.25, Mo 0.50.....	19.9	1.5	....	....
C .08-.18, Mn 0.30-0.60, Cr 1.75, Mo 0.50.....	37.2	....	....	....
C .08-.18, Mn 0.30-0.60, Si 0.50 max.....	41.0	4.3	....	....

Sulphur Corrosion Resistance—The type of corrosion resistance of commercial importance is immunity to the attack of various kinds of sulphurous gases—H₂S, SO₂, SO₃—found in furnace flue gases at high temperature. Calorized articles may, therefore, be used in furnaces which employ high sulphur fuels. Calorizing has wide acceptance in oil refineries and contact sulphuric acid converter heat exchangers. It is rapidly attacked, however, by aqueous solutions of mineral acids and, hence, not suitable at the low temperature end of furnace ducts where condensation of water vapor in the flue gases is likely to cause formation of sulphurous acid.

Table II
Hydrogen Sulphide Test

Type of Material	24 Hours at 1200°F.	
	Not Calorized	Calorized
	Weight Increase, Milligrams per Sq. Cm.	
C .08-.18, Cr 18, Ni 8.....	36.5	0.1
C .08-.18, Mn 0.30-0.60, Cr 5, W 1.....	175.6	0.5
C .08-.18, Mn 0.30-0.60, Cr 5, Mo 0.50.....	172.8	1.3
C .08-.18, Mn 0.30-0.60, Cr 5.....	183.4	0.5
C .08-.18, Mn 0.30-0.60, Mo 0.50.....	109.0	0.3
C .08-.18, Mn 0.30-0.60, Cr 2, Mo 0.50.....	124.3	0.5
C .08-.18, Cr 2.50, Mo 0.50.....	90.5	0.1
C .08-.18, Mn 0.30-0.60, Cr 1.25, Mo 0.50.....	101.3	0.7
C .08-.18, Mn 0.30-0.60, Si 0.50 max.....	173.5	0.6

Table II gives results of sulphur corrosion of some steels before and after Calorizing. The test was conducted in a muffle type furnace with hydrogen sulphide flowing continuously at atmospheric pressure.

High Temperature Creep Strength—The Calorizing process, by protecting the base metal from loss of cross section due to oxidation, extends the useful, high temperature working range of many low priced steels which do not possess oxidation resistance. As an example, a killed carbon steel containing C 0.08-0.18, Mn 0.30-0.60, and Si 0.50 required before Calorizing, 1400 psi. unit stress to produce 1% creep in 10,000 hr. at 1100°F., but after Calorizing this same steel under the same condition of test required 2,050 psi.

General Physical Properties—The iron-aluminum surface alloy is hard, but is sufficiently tough to exhibit about 5.0% elongation before development of surface cracks. This enables the surface alloy to bend with the steel when hot and the product is not subject to cracks under stresses within commercial limits.

Uses—Pots for salt, cyanide, and lead preferably operating at a bath temperature of not over 1550°F.; bolts to 1400°F. Tubes for air heaters, radiant steam superheaters, oil and gas polymerization. Furnace parts to 1400°F., glass lehrs and non-ferrous heating furnaces.

Fabrication—Except with light thicknesses of surface alloy of low aluminum content, such as employed on automobile exhaust pipes, cold fabrication of Calorized steel is not practical. Usually bending and forming must be performed at bright red heat, but unless the bending radii are liberal, cracking may occur. The Calorized steel will stand about 5% elongation before surface fissures appear.

Chromium Impregnation (Chromizing)

By F. C. Kelley*

The Process—The process consists of packing the material to be treated in a mixture of powdered alumina and chromium. Alumina is used to prevent the sintering of the powdered chromium into a solid mass. The amount of each material used may be varied, but a satisfactory mixture consists of 45% of dry alumina and 55% of chromium by weight. The material is usually packed in a tube or container of iron and then heated to 2375-2550°F. in hydrogen for three or four hours. The time may be varied according to the penetration and concentration of chromium desired.

The Atmosphere—A protective atmosphere like hydrogen is absolutely necessary to protect the chromium from oxidation and should be free from oxygen and water vapors. The chromium particles in contact with the material to be treated must be kept clean so diffusion may take place. The hydrogen should be of sufficient purity to reduce chromic oxide for this will preserve the chromium powder in the metallic state and prevent loss by oxidation. The hydrogen may be passed directly into the iron container holding the charge. The container should be provided with a vent to allow circulation of the pure hydrogen.

The atmosphere of the furnace may be commercial hydrogen with enough water and oxygen removed to protect the molybdenum winding from oxidation.

The Furnace—The temperatures used in this process demand a furnace capable of maintaining a high temperature over a long period. An electric furnace provided with a molybdenum or tungsten winding as the heating unit is used. A satisfactory type consists of an alundum tube wound with molybdenum wire. The tube is placed in a suitable furnace casing and surrounded with alumina powder which acts as a heat insulating material. The furnace casing should be tight to prevent the loss of hydrogen and the diffusion of air into it.

The Material—The material best suited for chromizing is a low carbon steel having a carbon content of 0.10-0.20%. Steels of higher carbon content may be used if the surface is first decarburized as by heating in hydrogen. Materials to be

chromized should have a clean surface so diffusion may take place freely. Machined parts should be free from oil, grease, or soap.

Structure of Coating—The layer of chromized material on the surface of iron treated by this process consists of large columnar grains. This structure is typical of many coatings formed on iron by diffusion processes. Elements such as aluminum, silicon, molybdenum, and tin diffusing with iron form coatings of similar structure.

Diffusion Rates—The penetration of the chromium with respect to time and temperature is best shown by curves in Fig. 1A and 1B.

Corrosion Resistance—Chromized iron has a high resistance to corrosion in salt spray, steam and under atmospheric conditions, and will stand up for long periods of time in 10% nitric acid without discoloring the solution. The chromium content of the diffused layer varies between 10 and 20%, according to the time and temperature of heating.

Other Methods—Becker, Hertel and Kaster have produced a chromium iron alloy by heating metallic chromium or ferrochromium and the iron to be chro-

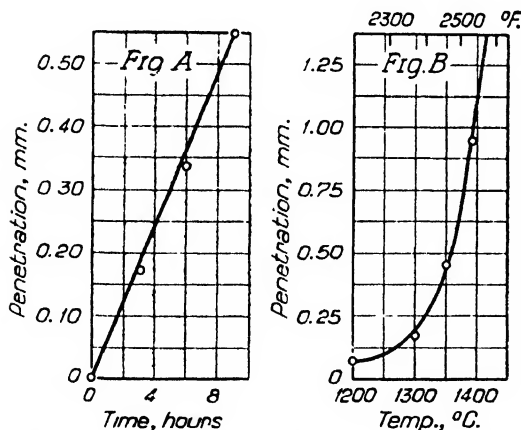


Fig. 1A—Curve showing the change in penetration of chromium with the time at a temperature of 2375°F.

Fig. 1B—Effect of temperature upon the penetration of chromium for a period of 3 hours.

*Research Laboratory, General Electric Co., Schenectady. Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

mized in a tube at 1750-1800°F. Pure dry hydrogen is first passed through the tube on heating. When the desired temperature is reached the dry hydrogen is then passed through fuming hydrochloric acid over the metallic chromium and finally over the iron to be chromized. The CrCl_3 vapor formed by the reaction between the hydrochloric acid gas and the chromium exchanges its chromium atom for an iron atom when it comes in contact with the iron surface, forming an alloy with the same characteristic structure as chromized iron. The grain size of the iron unaffected by the chromium must be smaller in this process than in the powder process due to the difference in the temperatures used. The resulting coating has the same physical and chemical characteristics as the coating produced by the powder process. It can be worked cold and resists the attack of nitric acid at all temperatures.

Diffusion is slowed up considerably below 1650°F., while above 1800°F. the grain size is large.

W. M. Mitchell secured a United States patent on a process for coating the surface of a steel ingot with a chromium iron alloy. He coats the surface of a mold with chromium using sodium silicate as a binder. When hot metal is poured into the mold it alloys with the coating and produces a chromium iron alloy on the surface. The ingot can then be rolled into sheets with a high chromium alloy on the surfaces. Castings with a high chromium alloy on the surfaces can also be made in the same way.

A British patent was granted to M. Fiedler for a process of coating a metal with a chromium rich alloy which consists of electroplating chromium on the surface of steel and then passing the plated article through a high frequency field to raise its temperature where alloying occurs between the base metal and the chromium plate. By this process iron pipe can be chromium plated on the outside and then passed continuously through a high frequency coil to heat it to about 2200°F., where alloying takes place between the chromium plate and the iron underneath.

Folliet and Sainderichin of Paris, France, were granted a United States patent on a cementation mixture for treating ferrous articles, comprised of an oxide of chromium, 2-10% of a chloride of chromium, and a quantity of finely divided aluminum. The aluminum content depends upon the amount of oxygen in the metallic oxide used. The articles to be coated together with the mixture in which it is packed are contained in a closed vessel and heated to 1825-2375°F. The action of the aluminum and the chloride results in an alloy between the liberated chromium and iron. The depth of penetration depends upon the percentage of metal oxides and the time at the working temperature.

Application—Chromizing has been used to protect turbine buckets against corrosion and erosion. Containers used for copper brazing tungsten contacts have been chromized so the copper would not braze the contacts to the container. The hydrogen atmosphere used for copper brazing usually contains enough water vapor and oxygen to oxidize the chromium on the surface and thus prevents the copper from wetting it.

Any steel parts which have to withstand atmospheric corrosion or the attack of nitric acid may be chromized to give satisfactory resistance. The chromized surface layer is practically free from carbon, and no attack occurs due to carbide precipitation.

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Zinc Impregnation

(Sherardizing)

By F. C. Kelley*

The original patent on this process was applied for in England on July 21, 1901, by Sherard Cowper-Cowles of London. The metallurgist of that time claimed that the zinc coating produced by this process was structureless but today we know that is not true.

Apparatus—The present day process is best carried out in tightly sealed drums to prevent as much oxidation of the zinc as possible. These drums are rotated in gas or oil fired furnaces to produce uniform coating of high density. Electrically heated drums having double walls properly insulated are also used. The electrical heating units are placed between the walls of the drum which is supplied with several containers made of coarse wire screen so that the charge in any container may be removed at any time. The drums in any case are not filled with powder. This allows the parts to be treated to rub against each other and the powder to change its position.

Sulphuric acid tanks or shot blasting apparatus is also necessary for cleaning the surfaces of material, the latter being preferable.

The Zinc Powder—The zinc dust should be as free from impurities as possible, especially from lead, although small amounts of silica or oxide of iron do not seem to be deleterious. Periodic chemical analysis is necessary, and on the basis of the results, the metallic zinc content is maintained between 80 and 92%, the remainder being zinc oxide and impurities.

One method used for the determination of zinc is the displacement of hydrogen from sulphuric acid. In this method the apparatus is carefully calibrated. The volume of gas liberated is corrected for temperature and pressure and also for the hydrogen evolved by iron and tin present in the powder.

Typical analyses of new and used dust are as follows:

	New Dust	Used Dust
Silica	Trace	0.43
Cu	0.01	Nil
Pb	0.99	0.81
Fe	0.39	1.16
Cd	Nil	Nil
Zn	97.98	84.50
ZnO	0.46	12.12
Total Zn	98.34	94.57

When new powder is used, it is first heated in the drums without any charge for a sufficient time to oxidize the powder so that the zinc content, when analyzed, comes within the specified range.

The used powder is analyzed frequently and new powder added when necessary to keep the zinc content above 80%.

It is necessary to remove the iron and iron oxide from the mixture by magnetic separation to maintain the uniform quality of the coating.

The particle size of the zinc powder, the analysis of which is given above, varies and the screen analysis is given below.

	Zinc, %
On 100 mesh	3.65
On 150 mesh	1.05
On 200 mesh	3.55
On 350 mesh	6.25
Through 350 mesh	84.50

Some of this zinc dust has a particle size as small as 1/40,000 to 1/50,000 of an inch.

Powder low in zinc (35%) gives a coating of sp.gr. 1 while that with a zinc content of 90% gives a coating of sp.gr. 6.75 when a temperature of 660-700°F. is used.

The powdered alloy of FeZn₁₀ has been used to a limited extent, but the temperature of heating must be higher than that for the powdered zinc.

*Research Laboratory, General Electric Co., Schenectady. Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

Sand was added to the powder in the early process to prevent caking at the higher temperatures and small amounts of carbon were added to limit the amount of oxidation of the zinc.

Temperature—The wide range of temperatures originally used gave widely varying results. Today the process is usually carried out within the temperature range of 660-700°F. which gives a satisfactory product. Lower temperatures result in a thinner zinc coating while higher temperatures give a coating with a greater iron content and not so resistant to the action of the atmosphere. The length of time required for sherardizing varies from 3-12 hr. depending upon the thickness of coating desired.

If the operating temperature is materially above 660-700°F. the coating is coarse and crystalline, but if much below this, the coating is relatively soft and porous. For the best coating it has been claimed that the charge should be heated as rapidly as possible to the temperature 660-700°F. In the case of the electrically heated drums this is done by the use of parallel series connections to the heater units.

The Coating—The color of the coating is gray. When the coating is cleaned by brushing or rubbing it has about the same color as pure zinc.

There is usually only one layer observed on the surface of the iron but by heating to higher temperatures a second layer is sometimes found. There has been some difference of opinion as to the composition of the single phase layer, some claiming it to be Fe Zn_7 , and others, Fe Zn_{10} . McCulloch found by heating iron foil in zinc dust for 45 days at 779°F. that the alloy formed contained about 6% of zinc. If he heated a similar piece of iron foil for two days at 689°F. he obtained about the same result. From these experiments McCulloch claimed the limit of the iron-zinc solid solution to be 6% of iron instead of the higher percentage usually shown in the constitution diagram. He gives 8-10% as the average iron content of good sherardized coatings. When the second layer appears it is much richer in iron, and Rawdon has suggested that it might be Fe Zn_4 .

All sherardized coatings are filled with minute cracks which are probably due to the large difference in expansion between the coating and the iron base.

The thickness of the coating produced in 3 hrs. at 660-700°F. is about 0.0025 in.

Fig. 1 shows a photomicrograph of an unetched specimen of sherardized iron with a light alloy coating of about 1.5 mils thickness. The fissures which show up so clearly are typical of all sherardized coatings.

The Cementation Process—Some have claimed that the coating is deposited from the vapor phase while others believe it is formed by contact between the metal and the powder.

Several years ago the author investigated the possibility of improving the process by carrying out the operation in a vacuum of 1 mm. pressure. It was found that there was little if any difference in the thickness or character of the coating if the charge was revolved when compared with samples produced in the regular way. This would seem to indicate that the coating was formed largely through contact of the powder with the iron. The vapor pressure of zinc is probably high enough to give a slight coating, but not enough to produce the thickness obtained in the regular process. Trood claimed that he obtained a much heavier coating in vacuum in a shorter length of time.

The fact that particles of iron oxide and silica are sometimes found imbedded in the coating supports the claim that the coating is formed by contact.

The Weathering of Sherardized Coatings—All sherardized coatings are anodic toward the iron with which they are in contact, but to a lesser degree than pure zinc on account of the iron which has diffused into them. Burgess found the potential for the alloyed coating was 0.20 to 0.25 volt against 0.50 volt for zinc. This accounts for the protective value of the zinc coatings.

The coatings low in iron content weather and gradually become dark and finally



Fig. 1—Sherardized iron—unetched.

almost black, but those with higher iron content become reddish due to the oxidation of the iron. The appearance of the red color does not necessarily mean that the iron underneath has been attacked. Those coatings high in iron however, do not resist the action of the atmosphere as well as those with lower iron content. The coatings high in iron will rust almost immediately in salt spray while those low in iron will stand up well. Those coatings which have 15-20% of iron break down rapidly when exposed to the action of the atmosphere, while those with 8-10% or less stand up well. The life of a good sherardized coating depends also upon the thickness of the layer.

The A.S.T.M. Committee A5 has published in its report for 1936 that sherardized, hot dipped, and plated zinc coatings of the same weight have approximately the same service life.

Application—Sherardizing produces a coating of uniform thickness and for this reason can be used on threaded parts like bolts and nuts. The threads are not filled up as is the case with hot dipped nuts or bolts. Allowance can be made for the coating when cutting the threads and after sherardizing they do not have to be rethreaded or tapped.

The principal application is for small steel parts such as bolts, nuts, and washers, or castings which have to resist the action of the atmosphere. Iron wire has also been coated, but the heavy coatings are brittle and crack off when the wire is bent.

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Silicon Impregnation

(Siliconizing)

By Harry K. Ihrig*

Introduction—A process of impregnating iron and steel with silicon has been developed.† The silicon-rich case, containing about 14% silicon greatly improves the resistance of the steel to corrosion, heat, and wear.‡ Other methods of producing silicon-rich cases on iron and steel have been studied experimentally,§ but have not resulted in processes of commercial importance.

Metals Treated—Forged, rolled or cast, low carbon steel with low sulphur content is suited for siliconizing. High carbon, low sulphur steels can be treated satisfactorily, but are impregnated more slowly. For example, S.A.E. 1045 steel requires about twice the time for a given depth of case that a low carbon steel requires. The silicon case on high sulphur free machining steels may be penetrated under corrosive conditions, with consequent cracking and spalling of the case due to attack of the underlying core. This attack is probably caused by a less resistant intergranular silicon-sulphide constituent.

White and malleable irons can be treated, but because of their high sulphur content, the resulting cases are, as a rule, not so corrosion or wear resistant as those produced on low sulphur steel. Gray cast irons, because of their high sulphur content and because they grow badly at treating temperatures, do not give a satisfactory case for many purposes.

As a rule, alloy irons and steels, particularly those with a chromium content, do not appear to treat so well as plain low carbon steels.

Preparation of Metals to Be Treated—The decarburized layer often found on forgings does not have to be removed. Sand imbedded in castings must be removed by pickling or sand blasting. Light mill scale does not have to be removed, but heavy annealing scale should be. Because the treatment temperature is above the critical point of irons and steels, it is advisable that all strains be removed before siliconizing; otherwise, they will be removed during the process and may cause distortion.

Silicon Impregnation Process—In the process covered by this article, the iron or steel is subjected to the action of silicon carbide and chlorine at temperatures of 1700-1850°F. Instead of silicon carbide, ferrosilicon or mixtures of ferrosilicon and silicon carbide may be used. Parts may be processed in a rotary or pot type furnace. The chlorine is added when the parts are at temperature. Ordinary carburizing equipment is used with only slight modifications and no inert or reducing gas is necessary during the silicon impregnation.

The exact mechanism of this reaction is not known. At temperatures up to 1850°F. it appears essential that the carbide be in contact with the article to be treated. It is believed that the chlorine liberates the silicon from the silicon carbide in the nascent form, whereupon it diffuses immediately into the article to be treated.

The case may be made any desired depth from 0.005 to 0.100 in. A case of 0.025 to 0.030 in. is usually produced on low carbon steel in two hours. Ordinary cylinder chlorine gas of about 99% purity is used. It is used in the same concentration as in the cylinder. The amount of chlorine gas used depends upon the size of the charge to be treated and the thickness of the case desired. The amount is determined experimentally for a given job and then held constant for the particular charge.

Structure and Composition of the Silicon Case—Fig. 1 is a photomicrograph of a silicon case. The analyses of the 0.010 in. cuts are shown to scale at the side. The silicon content is constant within less than one half of 1% for the first 0.040 in. of the case and then falls off gradually for an additional 0.020 in. or 0.025 in. This uniformity of silicon content in the outer layers makes it possible to grind the silicon impregnated parts to a considerable depth without destroying the best portions of the case.

A peculiarity of the silicon-rich case is that carbon from the outer portions of the article is pushed forward by the silicon and is concentrated underneath the silicon case.

Physical Properties—Siliconized articles show a case hardness of Rockwell B 80-85. Although not file hard, such parts cannot be machined or cut with a hacksaw by ordinary means.

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‡Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

†Commercially known as Ihrigizing.

Standard tensile test pieces cut from the same bar of S.A.E. 1015 steel show the following results before and after impregnation with silicon:

Untreated	
Elastic Limit, psi	37,750
Ultimate Strength, psi	60,550
Elongation in 2 in., %	38.5
Case cracked at, psi	.....
Treated	
	(.033 in. case)
Elastic Limit, psi	37,900
Ultimate Strength, psi	51,400
Elongation in 2 in., %	19.5
Case cracked at, psi	41,600

The case does not crack until the steel is pulled beyond the elastic limit. After the case cracks, the cross section is reduced and thus the ultimate strength is lowered. The ductility of the case is not so high as that of the core, but treated tubes are ductile enough to be rolled into headers. The case will not spall off under vigorous hammering. However, sharp corners should be rounded off to provide core support for all portions of the case.

The impregnation with silicon destroys all previous heat treatment. The case cannot be changed by any known heat treatment, but the core may be heat treated to give any properties possible with the particular type of base metal used.

Corrosion Resistance—Silicon impregnated articles are re-

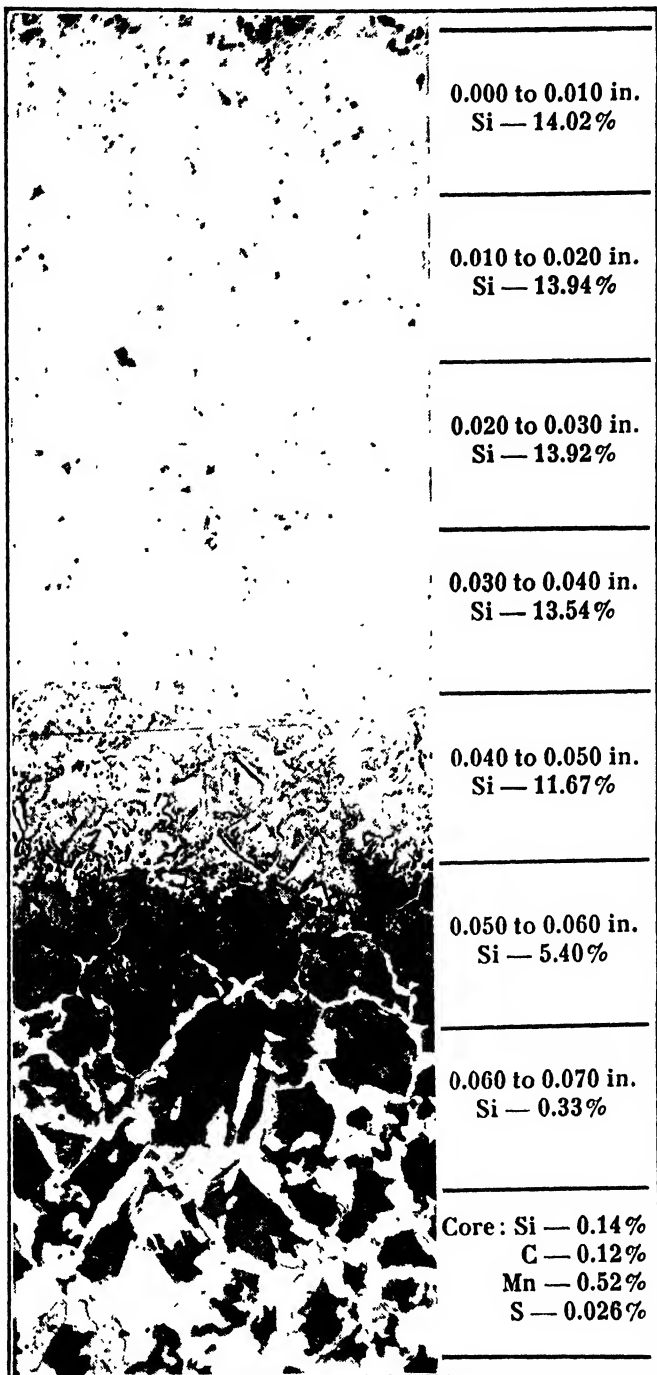


Fig. 1—Photomicrograph (100x) of silicon impregnated case with analyses of 0.010 in. layers.

sistant to nitric, sulphuric, and hydrochloric acids with a decreasing resistance in the order named.

Fig. 2 shows a treated bar which has been cut in two. One half has been boiled in dilute nitric acid until the entire core dissolved leaving only the case. The other half has been etched lightly to show the case.

In 10% boiling sulphuric acid, a $\frac{1}{2} \times 2$ in. round after treatment showed the following losses in weight:

1st 24 hours—3.1% loss	6th 24 hours—0.2% loss
2nd 24 hours—0.5	7th 24 hours—0.7
3rd 24 hours—0.3	8th 24 hours—0.7
4th 24 hours—0.4	9th 24 hours—0.7
5th 24 hours—0.4	10th 24 hours—0.3

Characteristic of high silicon alloys, the attack in the first 24 hours is relatively large, but after that it is greatly decreased. Carbon steel under these same conditions is entirely dissolved in about 18 hr., and 18-8 stainless steel in 24-30 hr.

Silicon-cased articles are not recommended for use in boiling mineral acids, because after the case is perforated the core is rapidly attacked.

The object of silicon impregnation is to produce an article economically that is resistant to corrosion. Because the alloy is only in the surface layers which are exposed to the corrosion, the core or major portion of the piece is of cheaper metal.

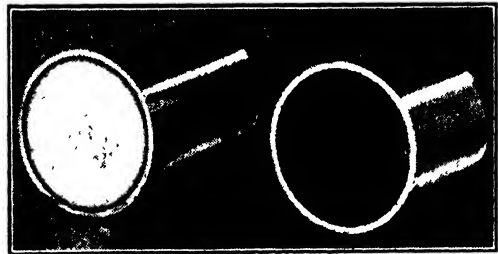


Fig. 2—Bar with silicon case; cut in half, one surface lightly etched and the other boiled in dilute nitric acid, leaving only the corrosion resistant shell.

Heat Resistance—The silicon case is resistant to scaling up to 1800°F. At this temperature excessive grain growth occurs in the steel core and the case tends to crack, but at temperatures of 1200-1600°F. long life has been obtained.

Wear Resistance—Under conditions of frictional wear, such as those to which shafts and cylinder liners are subjected, the silicon case has stood up well and the surface is particularly nongalling. Silicon case parts wear well against themselves. Where conditions of corrosion and wear exist together, the silicon case is especially effective.

Table I
Amsler Wear Tests
SAE 1015 Steel

10% Slippage and 1/16 in. Side Motion

Specimens	Rockwell C	Load, kg.	Revolutions	Loss in Dia., in.	Remarks
Carburized vs. Carburized	61	100	200,000	.005	Corners chipped
Sil. Impreg. vs. Sil. Impreg. Not boiled in oil	5	100	200,000	.001	No chipping
Sil. Impreg. vs. Sil. Impreg. Boiled in oil and wiped dry	5	100	1,000,000	.001	No chipping

10% Slippage, 1/16 in. Side Motion, and 1/32 in. Bump

Sil. Impreg. vs. Sil. Impreg. Boiled in oil and wiped dry	5	50	100,000	.000	No chipping
Carburized vs. Carburized	61	50	100,000	.001	Chipping started at 20,000 rev.

If a part, after treatment and finish grinding, is heated to 250-300°F. in a heavy oil, some of this oil is absorbed, and thus the treated part functions as a self lubricated bearing. This oil absorbing property is especially effective where outside lubrication is impossible. Table I gives the results of some Amsler wear tests on silicon impregnated test pieces in comparison to carburized ones. The effect of the oil absorption can plainly be seen.

The reason for the oil absorption is not certain, but it is believed that the case contains graphitic spots or voids left by the graphite that retain the oil.

The silicon case is not recommended for high velocity abrasion, such as found in sand blasting.

Distortion—A slight swell, that can not be adequately explained, occurs during the treatment of steel parts. This varies with the type of metal or alloy treated. Parts actually lose in weight during treatment because the heavier iron has been replaced by the lighter silicon, thus causing an over all loss in weight. The following table illustrates the changes in dimensions and weight on a 1 in. bar made from S.A.E. 1020 steel before and after treating:

	Before Treatment	After Treatment
Weight, g.	602	571.4
Diameter, in.	1.000	1.003
Length, in.	5.985	5.989

Because parts are not quenched after the silicon impregnation, little distortion occurs. Where the type of part permits, it may be straightened cold a few thousandths of an inch, or considerably more if heated to a temperature of about 1200°F.

Applications for Silicon Impregnation—Siliconized parts made from ferrous metals have given satisfactory service when subjected to corrosion, heat, or wear and the following will illustrate some of the applications:

Automotive water pump shafts, rocker arms, cylinder liners, and valve guides; valves, fittings and similar parts for the chemical, paper, and oil industries; forgings, steel, and malleable iron castings, thermocouple tubes, nails, screws, bolts, and tubing are siliconized where corrosion, heat or wear are problems.

Careful testing is essential before starting production to determine if the process is applicable to the particular service required of the part.

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Electroplated Metal Coatings

By William Blum*

Scope—The purpose of this section is to summarize those factors in the selection, application and testing of plated coatings that are likely to be of interest to those metallurgists and engineers who are not directly connected with plating operations. When more detailed information is required it can be found in the textbooks and articles referred to.

As practically all of the metals that are applied by electroplating are nonferrous, these processes might be classified under nonferrous metallurgy. Actually, the largest part of commercial plating is applied to iron and steel, though there are extensive applications of plating to copper, brass, nickel-brass, zinc, zinc-base die castings, and aluminum. To avoid duplication, the important commercial plating processes will be summarized in this section, with appropriate references to their applications to either ferrous or nonferrous metals.

The Selection of Electroplated Coatings—The choice of a plated (or other) coating for a specific purpose depends upon the advantages and limitations of that coating. Electroplating has been defined as "the electrodeposition of an adherent coating upon an electrode for the purpose of securing a surface with properties or dimensions different from those of the base metal." Among the specific reasons for applying plated coatings are the following:

1. To produce and retain a desired appearance, for example color and luster. This requirement usually involves also resistance to tarnish. In general (unless lacquer is subsequently applied) this aim can be accomplished by plating with the noble metals, such as platinum and gold, or with less noble, but passive metals, such as nickel and chromium. Silver resists oxidation,* but is readily tarnished by sulphur compounds, and copper is tarnished both by oxygen and sulphur.

2. To protect the base metals against corrosion. Because uncoated iron usually rusts on atmospheric exposure, it is customary to apply some protective coating. Plated metal coatings may protect iron in two ways.

- (a) The coating is less resistant to initial corrosion than iron, and therefore protects small exposed areas of iron by electrolytic action; in which process the coating is anodic, that is, it dissolves; and the base metal is cathodic, that is, is protected against corrosion. The two metals of this class that are applied commercially are zinc and cadmium. Coatings of both of these metals furnish prolonged protection to steel in mild or marine atmospheres, but are rather rapidly attacked in industrial locations, where sulphur compounds are present. Under the latter conditions, zinc lasts longer than cadmium coatings of the same thickness.¹ For either zinc or cadmium the protection is practically proportional to the thickness. Electroplated zinc furnishes about the same protection as zinc coatings of the same thickness that are produced by hot dipping or sherardizing.²

- (b) The coating is more resistant to initial attack than the steel. This is true of copper, nickel, tin, lead, chromium, silver, gold and practically all electrodeposited metals except zinc and cadmium. Such coatings furnish complete protection to the base metal only if they are impervious. If any pores exist, corrosion of the steel at those points is usually accelerated. The most practical method of decreasing the porosity and increasing the protective value, is by increasing the thickness of the coating.³ Of these metals, nickel is most commonly used to protect steel against corrosion. A preliminary coating of copper is frequently applied, partly because the copper may be more cheaply polished than the underlying steel or the superimposed nickel. The customary thin chromium layer increases the resistance to tarnish, but adds little to the protection against corrosion. Tin and silver coatings are used largely because of their resistance to foods and beverages. Lead is generally applied for resistance to sulphuric acid.

All plated metals applied commercially to zinc or aluminum are more noble than these base metals, and must therefore be thick enough to be nearly impervious in order to furnish good protection against corrosion. As a first approximation, about the same thickness of nickel, or of copper plus nickel, is required on zinc or aluminum as upon steel. On copper and brass, thinner coatings of nickel are usually adequate.

The electrochemical series of equilibrium potential is a rough guide to the

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ability of a metal coating to protect other metals against corrosion, but there are many practical exceptions. Although the standard potential of cadmium is less negative (more noble) than that of iron, a cadmium coating protects iron that is exposed through small pores. On the other hand, under equilibrium conditions, chromium is more negative (less noble) than iron, but, because chromium becomes passive in the air, it accelerates the corrosion of exposed iron.

3. To protect a base metal against some specified chemical reaction. The most extensive use of this type is that of copper plating to prevent certain parts of steel articles from absorbing carbon during case hardening. Experience indicates that the thickness of copper coating determines the protection afforded for any given period and temperature of hardening.⁴ It is probable that the increased thickness is effective by reducing the porosity.

A similar application, usually confined to laboratory practice, is the use of silver coatings to protect steel against oxidation during heat treatment. Chromium is helpful, but not apparently equal to silver for this purpose. Nickel plated steel is used in alkaline storage batteries and oxygen-hydrogen cells, because nickel resists alkaline solutions. Nickel and chromium coatings are used in the manufacture of films and plastics, because these metals resist most organic compounds.

4. To protect the base metal against wear, caused by either abrasion or erosion. (Erosion is here defined in the same sense as "surrosion," that is, the combined result of corrosion and abrasion.) Resistance to abrasion requires that the coating shall be harder and "tougher" than the base metal. Protection against erosion involves also ability to resist chemical attack by the surrounding medium. Chromium more nearly meets these requirements than any other single plated metal, and is extensively used for wear resistance on gages, dies, molds, printing plates, and certain cutting tools. (See the article on "Hard Chromium Plating" in this Handbook.)

5. To increase the dimensions. This process, known as "building up," may be applied to parts accidentally made undersize, or to worn parts. Coatings to serve this purpose must be at least as hard as the metal to which they are applied. The three metals commonly used are iron, nickel, and chromium. Iron has the advantage of cheapness (significant in large scale operations) and the fact that it can be subsequently case-hardened. Nickel is the most easily applied, and its hardness can be controlled over fairly wide limits. Chromium is most commonly used when greater wear resistance is desired than can be secured with the base metal alone. Two practical difficulties that have limited the use of building up (especially in America with high priced labor) are the selection and application of suitable "stop-offs" to prevent deposition on areas not to be built up, and the care needed to consistently secure the high degree of adhesion usually required.

The Specification and Testing of Plated Coatings—The principal properties of coatings that determine their value, and may therefore serve as a basis for specifications are (1) thickness, either average or minimum, (2) porosity, (3) adherence, (4) hardness, and (5) luster.

A—Methods of Test—(1) *Thickness*—The average thickness is estimated by stripping (dissolving) the coating from a known or measured area, and determining its amount by loss in weight or by chemical analysis of the resultant solution. The average thickness has been the basis of most plating specifications, but now is being replaced by requirements for a certain minimum thickness on significant surfaces.

The minimum thickness, or the thickness of coating at any point may be measured by: (a) Microscopic examination of a suitable cross section.⁵ (b) The "chord" method,⁶ in which the coating is cut through with a grinding wheel of known radius. (c) Methods depending upon rate of chemical reaction, such as the Preece test for zinc coatings,⁷ the "spot" test with concentrated HCl for chromium coatings,⁸ the "dropping test" for zinc and cadmium deposits,⁹ and the "jet" test for nickel coatings.⁹ (d) Nondestructive magnetic methods, which depend either upon the attraction of a magnet to the coating¹⁰ (for example to nickel on a non-ferrous base metal); or upon the reduction in attraction of the magnet by the presence of a nonmagnetic coating¹¹ such as copper, zinc, or chromium on a magnetic base metal such as iron or steel. Of these methods, the microscopic is the most reliable (except for very thin coatings) and is usually the basis of umpire tests.

The minimum thickness obtained on a given article depends upon, and can be controlled by, the average thickness, that is, the time and current density used; and the distribution of coating. The latter depends upon the throwing power of

the solution and upon the shape of the article and its position with respect to anodes and racks.

(1) *Porosity*—Small pores in zinc and cadmium coatings that are more than 0.0002 in. thick have little significance. Porosity of more noble coatings on steel may be detected and roughly estimated by some form of ferroxy test such as the ferroxy paper,¹³ and by the boiling water test,¹³ but the results are not sufficiently quantitative to be used in specifications. With the noble coatings, the salt spray test is principally a measure of porosity.

(2) *Adherence*—Poor adherence can be detected by deforming the specimen, for example by bending, twisting, hammering, extruding, or stretching. These methods do not yield quantitative results. The methods of Ollard¹⁴ and Jacquet¹⁵ for measuring adhesion require special specimens and are not applicable to finished products.

(3) *Hardness*—Most of the customary methods of measuring hardness are directly applicable to plated coatings only when the latter are much thicker than those used commercially, because with thin coatings, the results are influenced by the base metal. The results on thick coatings do not necessarily represent the properties of the thinner coatings usually applied in commercial plating. Measurements show that for each plated metal, it is possible to vary and control the hardness over a fairly wide range by altering the conditions of deposition. For example, electrodeposited nickel and iron vary in Brinell hardness number from about 150 to 400; and chromium from about 500 to 900. No simple correlation has been found between the results with each hardness test and the behavior in service.¹⁶ In those cases, such as intaglio printing plates, in which wear is caused principally by abrasion, the scratch hardness is at least roughly proportional to the wear resistance.

(4) *Luster and Reflecting Power*—Egeberg and Promisel¹⁷ express the brightness of a plane surface as the ratio of the specular reflection (in which the angle of reflection is equal to the angle of incidence, 45° in their tests) to the diffuse reflection (that is, the reflection at all other angles). This method is applicable only to plane specimens, but may be useful in research, especially upon deposits from "bright plating" solutions.

(5) *Protection Furnished Against Corrosion*—Continuous exposure in typical atmospheres¹⁸ yields results that are closely related to the life in similar service, but such tests require months or years. Accelerated corrosion tests are useful for comparing the behavior of similar coatings under conditions corresponding to those in the test.¹⁹ For example, the salt spray test yields results that may be similar to those in marine, but not in industrial locations.

B—Typical Specifications—Tentative specifications adopted by the American Electroplaters' Society and the American Society for Testing Materials²⁰ may be summarized as follows:

Nickel and Chromium Coatings on Steel.

	Type KS General Service	Type QS Mild Service
	Minimum thickness on significant surfaces,	
	Inches	Inches
Copper plus nickel.....	0.00075	0.0004
Final nickel	0.0004	0.0002
Average thickness* chromium (if required).....	0.00002	0.00002
Salt spray, continuous exposure.....	48 hr.	16 hr.

*It has been recently suggested that this requirement might be replaced by a minimum thickness of 0.00001 in. chromium, measured by the spot test with concentrated HCl.

Zinc or Cadmium Coatings on Steel.

Type LS—Zinc NS—Cadmium General Service	Type RS—Zinc TS—Cadmium Mild Service
Minimum thickness on significant surfaces,	
Inches	Inches
0.0005	0.00015

Important Factors in Electroplating—The quality, including appearance, adhesion, porosity and protective value of electroplated coatings, depends upon numerous factors such as:

Base Metal—It is not possible to apply high quality coatings to poor quality metals. The composition of the base metal should be known and controlled. The structure of the base metal may affect the reactions in cleaning and pickling processes, and the structure of the coating. The condition of the surface, including the degree and nature of the polishing processes, and the presence of pores, cracks, or inclusions, has a direct bearing upon the character and porosity of the coatings.

Preparation for Plating—It is necessary to have a chemically clean surface upon the base metal to secure good adhesion of deposits. The preparation usually involves "cleaning," that is, removal of grease and foreign particles; and "pickling" (for steel) or "dipping" (for nonferrous metals) to remove oxides or other compounds (including absorbed alkali), and in some cases to etch the surface. Methods of cleaning are described on page 1123, and of pickling on page 1131. In some cases surfaces are prepared for plating by sand blasting (page 1142) or rolling (page 1144).

Electrodeposition—In the actual plating process, it is desirable to control by appropriate measurements and tests:

a. The composition of the baths, including the concentrations of major constituents and of objectionable impurities. In general, it is not necessary to keep the major constituents more nearly constant than $\pm 5\%$ of the amounts present, and analytical methods that are accurate to $\pm 2\%$ are usually adequate. The permissible content of each impurity must be determined by experience under the conditions employed. The acidity or pH should be controlled in all except very strongly acid or alkaline solutions.

b. The temperature of the bath should be kept within specified limits, which are narrower for chromium than for other plating baths.

c. The average current density must be kept within desired limits, for the sake of uniformity in thickness and quality of coatings.

d. In many baths agitation permits an increase in the current density. Some agitation is secured by the movement of oscillating rods or continuous conveyors, but stronger agitation is sometimes obtained with air or with rotating electrodes.

e. In general, the anodes should be of such composition and structure as to maintain the metal concentration and the pH, that is the anode efficiency should be nearly the same as the cathode efficiency. In chromium plating and a few other operations where insoluble anodes are used, the metal content is maintained by replenishment.

Equipment—(a) *Electrical*—Practically all commercial plating is conducted with motor generator sets, usually with potentials from 6-12 volts, and with currents depending upon the area of work to be plated and the current density. In recent years, large copper oxide rectifiers have been used abroad for plating.

(b) *Tanks*—The tanks are usually constructed of (a) wood, used principally for rinse tanks; (b) steel, used for alkaline cleaning and for cyanide plating baths; (c) rubber lined steel, used for acid pickles, acid copper baths, and nickel baths; (d) lead lined steel or wood, used for sulphuric acid pickles, acid copper baths and chromium plating; and (e) acid proof stoneware, used for dips containing nitric acid and for small plating baths.

Typical Plating Baths and Conditions—The following concentrations and conditions are typical, but they may require changes to meet specific needs.

Copper Plating

(a) Acid bath, used in electrotyping, and for intermediate layers of copper, or for copper on brass.

Copper sulphate, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, oz. per gal.....	27
Sulphuric acid, H_2SO_4 , oz. per gal.....	8
Temperature, °F.	75-120
Current density, amp. per sq.ft.....	20-40

(b) Cyanide bath, used for plating copper directly on steel, as well as on brass or zinc.

Copper (cuprous) cyanide, CuCN , oz. per gal.....	3
Sodium cyanide, NaCN , oz. per gal.....	4.5
Sodium carbonate, Na_2CO_3 , oz. per gal.....	2
(Free sodium cyanide), NaCN , oz. per gal.....	1
Temperature, °F.	95-120
Current density, amp. per sq.ft.....	3-15

(c) Rochelle salt, cyanide bath, used especially for plating copper on zinc-base die castings.

Copper cyanide, CuCN , oz. per gal.....	6
Total sodium cyanide, NaCN , oz. per gal.....	7.5
Free cyanide, NaCN , oz. per gal.....	0.75
Rochelle salt, $\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 5\text{H}_2\text{O}$, oz. per gal.....	6
Sodium carbonate, Na_2CO_3 , oz. per gal.....	4
Temperature, °F.	130
Current density, amp. per sq.ft.....	30-40

Nickel Plating

(a) Plating on steel or brass at low current density.

Nickel sulphate, $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$, oz. per gal.....	16
Ammonium chloride, NH_4Cl , oz. per gal.....	2
Boric acid, H_3BO_3 , oz. per gal.....	2
pH	5.3
Temperature, °F.	70-90
Current density, amp. per sq.ft.....	10-20

(b) Plating on steel or brass, and over copper on zinc at high current densities.

Nickel sulphate, $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$, oz. per gal.....	30-40
Nickel chloride, $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, oz. per gal.....	6
Boric acid, H_3BO_3 , oz. per gal.....	4
pH, high	5-5.2
low	2-5.5
Temperature, °F.	100-150
Current density, amp. per sq.ft.....	20-50

(c) Plating directly on zinc die-castings.

"High Sulphate Bath"

Nickel sulphate, $\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$, oz. per gal.....	10
Sodium sulphate, Na_2SO_4 , oz. per gal.....	15
Ammonium chloride, NH_4Cl , oz. per gal.....	2
Boric acid, H_3BO_3 , oz. per gal.....	2
pH	5.5
Temperature, °F.	70-80
Current density, amp. per sq.ft.....	20-30

Chromium Plating (See also p. 1102)

Chromic acid, CrO_3 , oz. per gal.....	30-50
Sulphuric acid, H_2SO_4 , oz. per gal.....	0.3-0.5
(The sulphuric acid, or an equivalent amount of any soluble sulphate, should be in such concentration that the ratio $\text{CrO}_3/\text{SO}_4 =$ about 100.)	
Temperature, °F.	100-160
Current density, amp. per sq.ft.....	60-500

The temperature and current density should be so related as to give a cathode efficiency of about 12% for bright deposits and 16% for hard deposits. In general, the current density must be increased as the temperature is raised, and be slightly higher for hard deposits than for ornamental coatings. For example, at 113°F., current densities from 100-150 amp. per sq.ft. yield bright deposits, and from 150-200 amp. per sq.ft. yield slightly dull but harder coatings.

Zinc Plating

(a) Acid Bath.

Zinc sulphate, $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, oz. per gal.....	50
Aluminum chloride, $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$, oz. per gal.....	3
Sodium sulphate, Na_2SO_4 , oz. per gal.....	10
pH	3-4
(Organic addition agents are frequently used to produce brighter deposits).	
Temperature, °F.	70-95
Current density, amp. per sq.ft.....	20-50

(b) Cyanide Bath.

Zinc cyanide, $\text{Zn}(\text{CN})_2$, oz. per gal.....	8
Sodium cyanide, NaCN , oz. per gal.....	3
Sodium hydroxide, NaOH , oz. per gal.....	7
(Various addition agents, both organic and inorganic, are often used to produce brighter deposits).	
Temperature, °F.	70-95
Current density, amp. per sq.ft.....	10-30

Cadmium Plating

Cadmium oxide, CdO , oz. per gal.....	6
Sodium cyanide, NaCN , oz. per gal.....	16
(With organic and inorganic addition agents as brighteners).	
Temperature, °F.	70-95
Current density, amp. per sq.ft.....	10-30

Tin Plating

Sodium stannate, Na_2SnO_3 , oz. per gal.....	12
Sodium hydroxide, NaOH , oz. per gal.....	1
Sodium acetate, $\text{NaC}_2\text{H}_3\text{O}_2$, oz. per gal.....	2
Hydrogen peroxide, H_2O_2 (25 vol.), oz. per gal.....	0.3
Temperature, °F.	130-160
Current density, amp. per sq.ft.....	20-60

Lead Plating

Basic lead carbonate, $\text{Pb(OH)}_2 \cdot 2\text{PbCO}_3$, oz. per gal.....	20
Hydrofluoric acid, HF (50%), oz. per gal.....	32
Boric acid, H_3BO_3 , oz. per gal.....	14
Glue, oz. per gal.....	0.03
Temperature, °F.....	70-90
Current density, amp. per sq.ft.....	10-20

Iron Plating

Ferrous chloride, $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$, oz. per gal.....	40
Calcium chloride, CaCl_2 , oz. per gal.....	45
Temperature, °F.....	190
Current density, amp. per sq.ft.....	50

Brass Plating

Copper cyanide, CuCN , oz. per gal.....	3.6
Zinc cyanide, Zn(CN)_2 , oz. per gal.....	1.2
Sodium cyanide, NaCN , oz. per gal.....	7.5
Sodium carbonate, Na_2CO_3 , oz. per gal.....	4.0
Temperature, °F.....	90-120
Current density, amp. per sq.ft.....	2-5

Silver Plating

Silver cyanide, AgCN , oz. (troy) per gal.....	4.4
Potassium cyanide, KCN , oz. (avoir.), per gal.....	5.0
Potassium carbonate, K_2CO_3 , oz. (avoir.), per gal.....	5.0
Temperature, °F.....	70-90
Current density, amp. per sq.ft.....	2-10

Before plating silver on most base metals, it is usually necessary to plate them for a few seconds at a high current density in a more dilute silver cyanide bath known as a 'strike' solution.

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(No attempt has been made to include a complete bibliography. The papers cited are recent and readily available, and many of them contain summaries and extensive references).

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Industrial or "Hard" Chromium Plating

By D. A. Nemser* and W. E. Bancroft†

Definition—The chromium in "hard" chromium plating, as distinguished from decorative chromium plating is usually deposited in appreciable thicknesses directly on the base metal. This type of plate is finding wide industrial application. Ordinarily, the base is fully or semihardened steel. In some cases, however, successful applications have been made on soft steel, cast iron, and many nonferrous alloys. Fairly heavy deposits must be made on the softer base materials if heavy pressures are encountered in service.

The plate depth usually is in the range of 0.0001-0.040 in. or more. The heavier deposits are used chiefly for salvage purposes.

Hardness—The outstanding property of electrochemically deposited chromium is its resistance to wear. Schneidewind reports that the average deposit will show the following hardness values: Vickers-Brinell 625, Mohs 8, and scratch width with Bierbaum Microcharacter test of 2 microns. In employing these values, however, it must be borne in mind that the plating conditions have a profound effect on the hardness of plate. These figures must therefore be regarded as approximate.

Chromium plate manifests a file hard reaction to a temper testing file. Wear resistance far superior to that found with fully hardened tool or die steels is obtained.

Toughness—The plate is extremely brittle and should not be employed for tools subjected to shock. The toughness can be somewhat increased without depreciating wear resistance by heating to temperatures under 500°F. This treatment will rid the plate and steel base of occluded hydrogen. A temperature of 300-400°F. is ordinarily employed.

In this connection, it is well to consider that the deposited plate is really a solid solution "alloy" of chromium and hydrogen. Schneidewind has shown that the hardness remains constant until a somewhat critical range at 525-550°F. is reached. Beyond this, a marked falling off in hardness occurs, indicating the decomposition of the "alloy". The hardness decreases gradually at higher temperatures. At 1900°F. the plate will show a Mohs hardness of 4.5 and a Vickers-Brinell of 150. It is then considered fully annealed, manifesting properties similar to cast chromium, as it is soft, ductile, and malleable, and possessing extremely poor wear resistance.

Coefficient of Friction—The low coefficient of friction of chromium plate is also advantageous. It minimizes friction in metal to metal contact. The plate is characterized as being "slippery, greasy, and nonwetting".

Chemical Resistivity—Chromium plate is not affected by most organic chemicals, alkalies, sulphur, and sulphur compounds. Nitric acid will not dissolve it. The plate is readily attacked by hydrochloric acid and slowly by sulphuric acid.

Corrosion Resistance—Chromium plate does not tarnish or corrode in ordinary atmospheres. However, fairly thin deposits are apt to contain cracks and pinholes which permit corrosive elements to come in contact with the base metal. Proper control of plating conditions minimizes this tendency.

Melting Point—Chromium melts at 2822°F. and retains a bright surface up to approximately 900°F., therefore, serving well for some high temperature applications. Its coefficient of expansion, however, is less than that of most metals, and therefore, flaking of plate might occur, where the plated object is subjected to wide temperature changes.

Miscellaneous Properties—Chromium is nonmagnetic, which opens a field in rendering nonferrous electrical parts longer wearing. It prevents the sticking of resinous plastics, rubber, paper, and celluloid to forming molds. Chromium has approximately the same heat and electrical conductivity as aluminum, and approximately half that of copper and silver. Another feature favoring the use of chromium plate is its adaptability. It can be applied on the standard product with a minimum departure from established manufacturing routine. Chromium

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plate possesses a bright pleasing appearance, which aids materially in the marketing of the product.

Plating Method—It is not within the scope of this writing to give a detailed account of all the many factors which enter into the deposition of hard chromium plate. However, an attempt has been made to give a general outline of practices employed in plating the ordinary run of work.

Cleaning—Before plating, the work surface should be rendered chemically clean. Dirt, grease, and oil should be removed either with organic solvents or alkaline metal cleaner. The various manufacturers of these materials are thoroughly equipped to analyze any cleaning problem and supply the proper type of material. Scale, rust, oxide, and tarnish are removed by pickling or dipping in acid solutions. The most commonly used are hydrochloric and sulphuric acids. These may be used singly or combined, in varying concentrations and at varying temperatures, depending on the type and quantity of foreign matter to be removed. Sometimes electrolytic acid pickling is the only satisfactory way to remove heavy scale, especially on deeply recessed parts.

Sandblasting, hand scrubbing, polishing with emery cloth and buffing are useful adjuncts to the cleaning operation. Sandblasting, of course, roughens the surface but where the work is to be ground or polished after plating, this is not a disadvantage. In fact, on some types of alloy steels, sandblasting has been found imperative in producing a sound, tightly adhering plate. Buffing may be used to remove light rust, tarnish, and fingerprints. This operation leaves a film of grease which protects against further rusting while being racked up. It is easily removed in the cleaner. The authors realize that there might be some objection to the practice of buffing due to the smooth surface formed. However, their own practical experience indicates that buffing may be advantageously employed for certain cases.

Racking—Work to be chromium plated is usually racked in one of the following ways:

1. Parts which require only a comparatively thin plate (usually 0.0002-0.0003 in.) over the entire surface may be mounted on frame-like racks equipped with phosphor bronze spring wires, battery clips, bolts, or some other similar device, to hold work tightly. These racks are hung on the cathode bar between rows of flat lead anodes.

2. Parts requiring several thousandths of plate evenly distributed, as, for example, plug gages and shafts, may be assembled in connection with anodes made of sheet lead formed into shape conforming to that of the work and located a set distance from surface to be plated. Holes, such as ring gages and dies, may be plated by placing anodes made of lead wire or tubing in the center of hole.

3. In some cases, good results are obtained by placing a flat or curved lead anode before a straight cylindrical piece of work and rotating the latter while plating.

Parts, unless heavy, must not be hung on hooks or held loosely in the bath. Positive, tight contact must be maintained.

Conforming anodes should be mechanically connected to the work-holding fixture to insure uniform spacing but, of course, insulated from it electrically. Work should be held in such position that gas pockets are not formed and that drag out is not excessive. Racks may be insulated by coating with special "stop off" lacquer or wrapping with rubber tape and then lacquering.

When it is desired to keep certain sections of the work free from plate, this may be accomplished by wrapping with sheet lead or lead foil, lacquering, wrapping with tape or sometimes covering with sleeves or plates made of steel, copper, glass, or porcelain, depending on whether insulating or conducting properties are desired. If the work must remain in the plating tank for appreciable time intervals, the tape should be covered with lacquer to prevent its disintegration.

Plating—After work has been properly cleaned, pickled, and mounted in racks, it is given the following or some similar treatment:

1. Two to three minutes in metal cleaner to remove dirt, oil, buffing compound, or fingerprints. Use direct current, 6-8 volts, and operate at about 200°F. with work as cathode. When using frame racks containing work only, the iron tank lining may be used as anode although separate steel plates hung alongside the tank are recommended. When using composite assembly containing conforming anodes, these anodes are connected into the circuit on positive side.

2. Cold water rinse.

3. One half to two minutes with reverse current in a solution of sulphuric acid of 50° Baumé at about 6 volts. This slightly etches the surface of work and provides better adherence.

Note—A solution of warm chromic acid (20° Baumé) with reverse polarity at about 6 volts may be used here. In this instance no subsequent rinse is necessary and the work may go directly into the plating bath.

4. Cold water rinse, if sulphuric acid etch is used.

5. Immerse in plating bath at low current and build up to plating current slowly, taking about 5 min. Plate under carefully selected current density and temperature conditions the length of time required to get desired thickness of deposit.

6. After plating, rinse in clean, cold water, then hot water and finally dry, using air blast or hardwood sawdust. If more convenient, work may be unracked and rinsed before drying.

Plating Solution—The plating solution may be made according to one of the following formulae:

Chromic acid	250 g. per l.	Chromic acid.....	400 g. per l
Sulphuric acid.....	2.5 g. per l.	Sulphuric acid.....	4.0 g per l
Baumé	21°	Baumé	31°

Other compounds containing the SO_4 radical may be used in place of sulphuric acid, the important point being that the ratio between chromic acid and sulphate radical be fixed and controlled within narrow limits. Variations in ratio usually necessitate changes in some of the other factors.

The plating solutions are best operated warm, somewhere between 100 and 150°F.; 120°F. is a satisfactory temperature. A uniform temperature must be maintained. In general, the higher temperatures necessitate higher current densities to produce equivalent results. It is important for good results to co-ordinate composition of solution with temperature and current density.

Current Density—Amperes per unit of area on work surface is the most important factor in determining plating speed. Too low a current density tends to give a milky deposit. The correct current density yields a bright plate while one which is too high gives a frosty or burnt deposit. A bright plate offers the most satisfactory all-around service. A synchronous motor generator set is desirable to supply the plating current.

Stripping—It often becomes necessary to strip off chromium plate. The most common method of handling this is to immerse the plated object in a cold solution of equal parts by volume of hydrochloric acid and water. This is suitable for any base metal which is not readily attacked by hydrochloric acid. Steel and cast iron are etched but little in this solution if the work is removed as soon as the chromium is entirely dissolved.

Stripping can also be accomplished by employing a sodium carbonate solution, 6-8 oz. per gal., with reverse current and steel cathodes. This solution is extremely desirable for steel and cast iron.

A warm chromic acid solution at 18° Baumé with reverse current is also employed.

Cold sulphuric acid made up of 1 part of water and 3 parts of sulphuric acid with reverse current is particularly good in stripping chromium from zinc and aluminum bearing base metals.

Health Hazard—The voluminous evolution of hydrogen and oxygen during plating mechanically carries a fine spray of plating solution into the air around the plating tanks. The chromic acid contained in this spray may cause severe irritation of the mucous membranes of the nose and throat if inhaled. In order to prevent this hazard, it is advisable to provide adequate exhaust on the plating tanks. A lateral forced draft exhaust system is preferred.

Skin lesions in contact with chromic acid tend to form painful and slow healing chromium ulcers. It is imperative, therefore, to properly protect cuts. A 5% solution of sodium bisulphite or similar reducing agent should be available for neutralizing chromic acid on the hands and arms.

Applications—Gages, tools, and machine parts are plated to increase their surface hardness and give longer life. Cylindrical plug gages, with a residual plate of 0.0015-0.002 in. after finishing to size, often give five times or more the wear obtained with the best grade of hardened tool steel unplated. Taps, reamers, milling

cutters, metal slitting saws, and drills when used on bakelite, hard rubber, bronze, aluminum, fibre, asbestos, copper, cast iron, steel of various composition, wood, and other materials give greatly increased wear life and operate easier when plated.

As a "putting on tool" and salvaging medium in the machine shop chromium plate has no equal. Shafts, arbors, quills or spindles, accidentally machined or worn undersize, may be quickly, easily and effectively brought back to normal. Likewise, holes in gears, cutters, bushings, or dies may be reduced in diameter by almost any amount. On expensive parts salvaging with chromium plate usually represents only a small fraction of the replacement cost and is much quicker.

Mechanics' tools and other items of hardware such as micrometers, calipers, scales, drills, saws, feeler gages, chisels, and scrapers, which are not subjected to outdoor exposure, are greatly improved by a coating of chromium (0.0002-0.0003 in.) directly on the steel base.

Drawing dies and mandrels when chromium plated give 3-5 times the life of bare dies and mandrels in drawing copper, steel, nickel, gold, silver, platinum, and their alloys.

Molds for the various plastic materials, porcelain, glass, and rubber, are greatly benefited by a deposit of chromium. The bright finish is preserved much longer and the plastic material does not stick to the mold, while pitting is reduced or entirely eliminated. The mold wear is reduced and in general the molded product has a better appearance.

Rolls for sheet brass, copper, rubber, celluloid, and paper are being chromium plated quite extensively. The advantage is longer life and increased efficiency due to elimination of sticking and tearing.

Printing and engraving dies are another good subject for chromium deposits, a hard, nondistorted surface being obtained on soft bases such as copper or iron.

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Tinning of Steel

By Bruce W. Gonser*

Ferrous materials are usually tinned by hot dipping or immersing the product to be coated in a molten tin bath. Although not so extensively used, other methods are sometimes used as electrodeposition, metal spraying, or fusing a tin powder coating over the material.

In the tinning of ferrous products during recent years 91% of the tin consumed has gone into the production of hot tinned low carbon steel sheet, 3½% for tinned wire, and 4½% for the tinning of cast iron and miscellaneous parts.

The Manufacture of Hot Dipped Tin Plate—The importance of the United States tin plate industry is indicated by the 1937 production of 2,418,190 long tons. Over the last five years it has consumed an average of 22% of the world's production of tin.

The regular grade of thinly coated tin plate is known as coke plate. The composition of the steel used varies, but may contain from 0.05-0.10% C, 0.20-0.45% Mn, about 0.08% P for pack rolling or less than 0.015% for cold rolling, practically no silicon in rimming steel, and from about 0.03-0.05% sulphur. Various single impurities or combinations in the steel used for tin plate may have a marked effect on inhibiting or promoting corrosion in containers used for food. There is no universal specification for sheet for tin plate, since the composition and degree of cold work after annealing must be varied to meet specific uses. Thus, for some food containers the copper content may be limited to below 0.10%, and sometimes a limit is placed on P and Si.

For details on the manufacture of hot and cold rolled strip and sheet, see page 818.

Preparation of Sheet for Tinning—In preparation for tinning both cold reduced and pack rolled sheets are given a "white" pickling in a 3-6% sulphuric acid solution at about 160°F. After washing, the sheets are transferred to portable boshes or tanks containing water slightly acidulated with hydrochloric acid where they are kept wet, ready for tinning. Strip or sheets that have been bright normalized in controlled atmosphere may be placed directly in the boshes for immediate tinning. The base material is always introduced into the tin pot while wet.

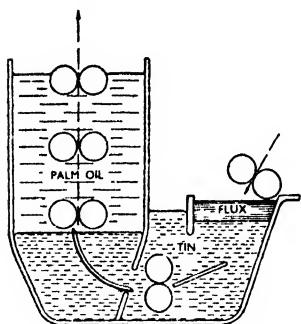


Fig. 1—Simplified diagram of pot for making tin plate.

Tinning—With the exception of a small amount of exceptionally heavily coated plate, tin plate is made in automatic tinning machines. These machines feed the base plate through a flux of zinc chloride into a tin bath and up through a palm oil compartment where excess tin is removed (Fig. 1). Auxiliary equipment carries the sheet through proper cleaning attachments where part or practically all of the adhering palm oil is removed and the plate is polished. The pot and rolls of the tinning machine accommodate 2 or 3 sheets to be tinned side by side at the same time. The tin bath of 5-7 tons of first quality tin is usually heated near the entrance end by immersion gas heaters.

Base plate for tinning is automatically fed into the first rolls of the tinning machine by auxiliary equipment which carry a sheet at a time from a storage tank at the front of the pot to an arrangement of rolls in the tin pot. Several sets of conveying rolls and directing baffles force the plate through the flux, the molten tin, under a dividing partition, and into the palm oil compartment. The rolls in the palm oil remove excess tin as they convey the sheet out of the tin pot. The rolls in the tin and palm oil baths are coated with tin, and those in the palm oil are equipped with fixed scrapers of asbestos or soapstone. These aid in removing tin and tin-iron "scruff" which adhere to the rolls from contact with the tin plate. The palm oil rolls are held against the sheets by slight spring pressure.

Palm oil acts as a flux to aid in obtaining good distribution of tin and serves as

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a cooling and protective medium so that the emerging tin quickly freezes without oxidizing. The temperature of the palm oil bath is kept as low as possible (by recirculating) preferably 460-470°F. at the top of the bath. At higher temperatures the palm oil readily polymerizes, which may cause yellow streaks in the tin plate. Sumatra palm oil is generally considered to be the best as it is of more uniform quality and contains a maximum of 5 or 6% oleic acid compared to perhaps double this amount for the African product. The two grades are sometimes mixed. In starting a tin pot some used oil is always mixed with new oil, usually in a ratio of 2 parts used to 1 part new. The average tin pot carries about 1000 lb. of palm oil in the exit compartment.

Steel sheets are passed through the tin pot at the rate of 25-30 f.p.m. The temperature of the bath is governed by the speed of tinning. This may vary from about 575-650°F. at the entrance end of the bath and be 100°F. lower near the palm oil compartment. Some tin is lost as dross and in concentrations of tin along the edges, particularly at the bottom or "list" edge of each sheet, hence the yield as calculated from the tin on the finished sheets near the center is only 85-90% of the tin consumed. Thus an average coating of 1.35 lb. per base box of tin as measured by the consumer may mean a calculated coating of 1.52 lb. based on the tin consumed in the mill.

Removal of palm oil from a finished plate may be effected by absorption in a dry material such as bran or by the use of an alkali cleaner or a combination of the two. Dry flannel rolls may be used for final cleaning. Practically complete oil removal is desired when the plate is to be lithographed or enameled but in other cases a residual film of oil may be desirable to preserve the finish or act as a lubricant in stamping operations.

Classification of Tinned Sheet—Sheets are inspected for finish and classified into various weights. Sheets having no visible defects are termed "primes", those with slight flaws are termed "seconds". "Menders" have more severe defects but are in general salvaged by straightening, cutting away damaged portions, or re-tinning. Waste sheets having prohibitive defects, such as badly crumpled sheets, are sent with scrap to be detinned. The proportion of prime sheets produced varies widely from time to time but in general will average about 85% of the total, with roughly 10% of the production going to seconds and for retinning, and 5% to waste.

Tin plate is measured and sold by the base box as defined in Table I, which also gives a tabulation of some of the weights and thicknesses of common tin plate. The tolerance on specified dimensions is usually $\frac{1}{8}$ in. Standard coke plate in the United States carries about 1.35 lb. of tin per base box or a coating of tin about 0.00007 of an in. in thickness. Better grades carry 1.50 and up to 1.75 lb. per base box.

Testing Tin Plate—Since practically all hot dipped tin plate is used in can making or closures for cans and bottles, its resistance to corrosion is an important property and is frequently tested at the tin mill as well as by the fabricator. The best test method is by actual performance records. Accelerated tests are made by maintaining the packed container at an elevated temperature. An even more accelerated test being rather widely used is to measure the time for a definite amount of hydrogen to be evolved when the tin plate is submitted to the action of warm dilute hydrochloric acid under standardized conditions.

Charcoal Plate—Heavier coatings of tin than those normally used in can making are designated as charcoal plate, a term originating in the superior quality of base plate once made by means of charcoal reduction.

Charcoal plate is tinned by machine in the same general manner as previously described, but with wiping rolls so adjusted that the tin coating left is relatively great, as 2-4 lb. per base box. For similar or for heavier coatings, hand dipping or a combination of hand and machine operation is used. More tin is made to adhere by dipping in molten tin kept at a relatively low temperature, then dipping in palm oil. Sometimes heavy coatings are produced by redipping at least once in another tin bath of higher purity. In this way coatings up to about 7 lb. per base box are obtained and even heavier coatings can be made.

Terne Plate—The steel sheet base forterne plate is prepared in the same way as in making tin plate. Much of the thinly coated terne plate is made in the same way and with the same machinery as is used in making tin plate. The only difference is that a terne metal bath contains an alloy of tin and lead, and the temperature of the bath is somewhat higher, also, a flux of zinc ammonium chloride is sometimes used in place of zinc chloride. Terne plate, such as that used in making

Table I
Coke Tin Plate Weight-Thickness Table

(A base box of tin plate, the standard of measurement and value, consists of 112 sheets of 14 x 20 in. plate, or 31,360 sq. in. of any size.)

Base Box Weight, lb.	Symbol	Approximate Weight of Sheet per sq. ft., lb.	Approximate Thickness of Sheet, in.	Nearest U. S. Standard Gage
55	..	0.253	0.0063	38
60	..	0.276	0.0069	36
65	..	0.298	0.0075	..
70	..	0.321	0.0080	35
75	..	0.344	0.0086	34
80	..	0.367	0.0092	33
85*	..	0.390	0.0098	..
90*	..	0.413	0.0103	32
95	..	0.436	0.0109	31
100	ICL	0.459	0.0115	30 1/4
107	IC	0.491	0.0123	30
112	..	0.514	0.0129	..
118	..	0.542	0.0136	29
128	IXL	0.588	0.0147	..
135	IX	0.620	0.0155	28
139	DC	0.638	0.0160	..
148	2XL	0.680	0.0170	27
155	2X	0.712	0.0178	..
168	3XL	0.771	0.0193	26
175	3X	0.804	0.0201	..
180	DX	0.827	0.0207	..
188	4XL	0.863	0.0216	25
195	4X	0.895	0.0224	..
208	5XL	0.955	0.0239	..
210	D2X	0.964	0.0241	..
215	5X	0.988	0.0247	..
228	6XL	1.047	0.0262	24
235	6X	1.08	0.0270	..
240	D3X	1.10	0.0276	..
248	7XL	1.139	0.0285	23
255	7X	1.125	0.0293	..
268	8XL	1.230	0.0308	..
270	D4X	1.240	0.0310	..
275	8X	1.263	0.0316	22
295	9X	1.355	0.0339	21
315	10X	1.447	0.0362	20
335	11X	1.539	0.0385	..
355	12X	1.631	0.0408	19
375	13X	1.722	0.0431	..
395	14X	1.814	0.0454	18
415	15X	1.906	0.0477	..
435	16X	1.998	0.0500	..

*Most used.

Weights of 55-65 lb. per base box are often designated as taggers' tin. Plate most used by can makers is covered by the weight range between 80 and 135 lb. per base box.

lubricating oil containers, contains from 18-25% tin. The coating for such cans is very thin, amounting to 1.15-1.25 lb. per base box which is only 70% the thickness of similar weights of tin plate.

Common "roofing tin" is heavily coated, hand dipped, terne plate which is usually designated as "short terne" to differentiate from the "long terne" or larger sheets. The composition of the base plate is usually selected with some regard to atmospheric corrosion resistance and is frequently machine coated with the terne mixture as part of the preparation for hand dipping. For roofing, a 25% tin-75% lead bath is commonly used. Sheets are dipped singly in one or two molten terne baths then into palm oil. The coatings are designated in terms of lb. per double base box, a double base box consisting of 112 sheets 20 x 28 in. The range of coatings varies from 12-40 lb. on this basis. Some indication of the thickness of coating may be noted by the size of the spangle or mottle. This decreases with an increase in coating thickness if the conditions of manufacture are similar. The size of mottle may be varied, however, by changing the rate of cooling.

Long ternes are machine coated sheets of comparatively large size. The sheets are frequently made in galvanizing rather than tinning mills and are similar to galvanized sheet in size. As with thinly coated terne plate, the base metal is passed through a zinc chloride or zinc ammonium chloride flux, through a terne

metal bath, and through a palm oil finishing compartment, by machine. The coating obtained is normally 8 lb. per double base box or under.

Terne metal is more expensive than zinc, but much cheaper than tin. Its advantage lies in the fact that it has certain of the properties of tin at a much lower cost. Under alternating exposure to air, it will remain bright where zinc will form oxides and carbonates. Therefore, terne plate is used for gasoline tanks, where any products of oxidation might clog the fuel line. The surface of terne plate is soft and has a greasy feel. The metal will not flake off, is very ductile, and seems to have considerable lubricating value. Thus, terne plate is used for deep drawing operations where a corrosion resistant material is desired. Its bright attractive finish makes it well suited to articles where appearance and corrosion resistance are both necessary, such as in burial caskets. A further advantage lies in the fact that it can be painted without weathering, which makes it an ideal roofing material.

Miscellaneous Hot Tinning—Wire and narrow strip are hot tinned continuously. The excess tin is removed by running the wire or strip through a wiping fixture, similar to a die, which is packed with asbestos or charcoal. This gives a thin coating, usually amounting to less than 0.00005 in. in thickness or about 0.025-0.035 oz. per sq. ft. of single surface. (With strip this weight would be doubled to give weight per sq. ft. of material, or the equivalent of 0.6-0.9 lb. per base box of tin plate.) For heavier coatings, other means of wiping, such as steam jets, compressed air, and a strong counter current flow of palm oil, have been suggested and used to a limited extent.

Preparation of wire and strip consists essentially of cleaning or pickling and passage through a zinc chloride flux before entering the pure tin bath. Since no palm oil is used the surface of the tin bath should be covered with charcoal to avoid oxidation. Strip tinned continuously in this way seldom exceeds 6 in. in width at present.

Fabricated articles are degreased before tinning by vapor cleaning or other suitable methods. This is followed by pickling in hot dilute sulphuric acid, temporary storage in dilute hydrochloric acid, as in making tin plate, fluxing and tinning.

Zinc chloride or zinc chloride containing a slight amount of ammonium chloride is a positive flux which is widely used in tinning fabricated articles. Molten tallow is sometimes used for fluxing. Usually the products to be tinned are first immersed in a preliminary tinning bath, then immersed in a second tinning pot to secure a better coating. In this way much of the iron-tin dross that forms remains in the first pot and the second pot can be maintained with a purer tin bath. The articles may be brushed or wiped while the tin coating is still fluid to assure complete coverage, then redipped momentarily to leave a free, smooth surface. As a final finishing operation, the articles are either withdrawn through a palm oil or molten tallow division of the final tinning pot or dipped in a separate bath of such material to permit drainage of the tin coating. The amount of tin adhering depends, of course, largely upon the temperature of this finishing bath and the time permitted for drainage, but the coating is always heavy compared to standard coke tin plate. A finishing touch is usually given by dipping the edge or bottom portion of the article, to which excess tin has drained, into a hot tin bath to remove the heavy tin concentration at this point. Cloth, bran, or sawdust may be used for the final polishing and grease removal.

Cast iron parts are not readily tinned due to the graphite in the iron and the difficulty in pickling to give a clean surface. Where possible, sand blasting or other mechanical means to effectively remove the casting skin is best. This is followed by pickling in warm sulphuric acid (5 or 6%) containing an inhibitor, storage in dilute hydrochloric acid, fluxing in zinc chloride containing up to 35% ammonium chloride and tinning in the general manner described for fabricated articles. Frequently a cold 5% hydrofluoric acid pickle is needed to remove residual sand. Surface decarburization does not always help in making the casting more easily tinned but an intermediate layer of pure iron, copper, or nickel which may be plated on electrolytically or by replacement is an advantage.

Retinning—Retinning used parts is fundamentally a repetition of primary tinning except that more attention must be paid to mechanical cleaning or to pickling the spots that have become rusted. For local repairs on large sections it is frequently much easier to clean mechanically and metal spray with tin than to dismantle and retin. By following normal soldering procedure prefaced by thorough

cleaning, and using pure tin in place of solder, it is often practical to repair small defects in place without the necessity for retinning the whole article.

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(These are recommended for supplementary technical information and do not necessarily indicate the source of information from which the foregoing discussion has been written)

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Zinc Coatings

By W. M. Peirce*

Zinc coating, or galvanizing, as it is commonly termed, is an old method of protecting iron and steel against corrosion. It is applied to a greater tonnage of steel products than any other metallic coating method and provides the most economical protection for the broad field where it is properly applicable. The major established applications of zinc coating on steel products are: Roofing and siding sheets, wire and wire products for all outdoor exposure, hardware for outdoor use, pipe and conduit, and exposed structural steel. In short, wherever steel is exposed to atmospheric corrosion, zinc coating is a standard and effective method of protection.

The effectiveness of zinc coatings depends, first on the relatively slow rate of corrosion of zinc as compared with iron and the much less objectionable appearance of the white, nonstaining corrosion products of zinc as compared to iron rust, and second, to the electrolytic protection afforded to iron by zinc. The latter factor prevents corrosion of the iron from occurring at minor discontinuities in the zinc coating such as sheared edges of sheets, cut ends of wire or abrasions in the surface. This electrolytic or "sacrificial" protection extends away from the zinc coating over exposed iron surfaces for a distance of as much as $\frac{1}{4}$ in. The distance varies with the properties of the moisture film as an electrolyte, being a maximum under such conditions as the presence of salt water.

Zinc coatings yield the longest life under rural exposure conditions where the air is free from sulphur gases and other industrial fumes. They give very satisfactory results in salt air exposures. They are most rapidly attacked in highly acid industrial atmospheres but are nevertheless widely used in such atmospheres. Frequently the combination of a zinc coating and an acid resisting paint or other organic coating is most effective, the zinc forming a better base for the organic coating and preventing its rapid failure by undercutting corrosion when the organic coating is penetrated.

When zinc coatings are to be painted for decoration or protection it is desirable to use a suitable primer such as a zinc dust primer which does not lose adherence on aging. The adherence of ordinary paints is improved by weathering of the zinc surface or by etching it chemically. Phosphate treated galvanized sheets are also on the market to which ordinary paint adheres well.

Zinc coatings are occasionally subject to an abnormal type of corrosion resulting in bulky white corrosion products. This originates from contact with water without free access of air. Galvanized sheets should be stacked on edge rather than flat to prevent rain or condensed moisture from being held between the sheets which may cause this type of corrosion. Zinc coated material which is to be used where "sweating" or other exposure to stagnant water may occur can be protected by a chromate surface treatment which has been developed for this purpose.

Since under the exposure conditions where zinc coatings are used, zinc has an appreciable rate of corrosion and since the coatings which can be readily applied are measured in one or two thousandths of an inch or less, it is obvious that the life of the coating will not be indefinite but will be determined by the thickness of the coating. Many comprehensive researches have shown that all other factors such as the method of applying the zinc coating, the purity of the zinc, and the degree to which it is alloyed with the iron are minor in determining life as compared to the thickness of the coating.

Zinc coatings are measured in ounces per sq.ft. of surface for all products except sheet. In the case of sheet, the weight of coating is stated in terms of ounces per sq.ft. of sheet which, since the sheet is coated on both sides, is twice the average weight of coating per sq.ft. of surface. The terms "Regular", "Tight Coat", and "Extra Tight Coat" as used in the trade refer to relative freedom from visible flaking of the coating when bent. Since this tightness of the coating to the base is ordinarily achieved by reducing the weight of coating, the terms have come to connote varying weights of coating—the "extra tight coat" corresponding to the thinnest coating. Weights of coating for many classes of galvanized products have been specified by the A.S.T.M. and are given in Table I. For a description of the methods of properly measuring the thickness of coating (which varies in uniformity

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to a degree dependent on the method of application), the A.S.T.M. specifications should be consulted.

Table I
Nominal Weights of Coating for Sheet*
As given in A.S.T.M. Specifications

Galvanized Sheet	8-16 Gage	Class A 2.75	Class B 2.50	Class C 2.00
"	18-22 "	" 2.75	" 2.50	" 1.75
"	24 "	"	" 2.50	" 1.50
"	26 "	"	" 2.25	" 1.25
"	27 "	"	" 2.00	" 1.25
"	28 "	"	" 1.75	" 1.25
"	29 "	"	" 1.50	" 1.25
"	30 "	"	" 1.25	" 1.25

*Weight of coating on two sides expressed in ounces per sq.ft. of sheet.

Minimum Weights of Coating for Wire^b
As given in A.S.T.M. Specifications

Telephone and telegraph wire and tie wire.....	{0.109 in. Diameter and above	0.8
R.R. right of way.....	{0.083 in. " "	0.7
Farm field fence.....	{0.148-0.192 in. Diameter	0.6
Barbed wire	{0.148-0.192 in. " "	0.5
Chain link galvanized after weaving.....	{0.098-0.135 in. " "	0.35
	{0.080-0.105 in. " "	0.35
	{0.120-0.192 in. " "	1.2

Strand	Extra or Double Galvanized	Galvanized Common
	0.188-0.207 in. 0.90	0.145-0.207 in. 0.40
	0.104-0.165 in. 0.80	0.080-0.120 in. 0.30
	0.093 in. 0.70	0.041-0.072 in. 0.15
	0.080 in. 0.60	
	0.062-0.072 in. 0.50	
	0.041-0.052 in. 0.40	

^bWeight of coating in ounces per sq.ft. of surface.

Table I should not be construed as representing the maximum weight of coating desirable for every application nor the maximum obtainable.

Zinc coatings are commercially applied by four methods. The oldest and most widely used is hot dipping. In this process the steel is first pickled in sulphuric or hydrochloric acid to remove all scale then washed to remove iron salts and finely divided iron. To be completely effective, this must be combined with scrubbing. Any iron salts or finely divided iron left on the surface form dross in the galvanizing pot. The work is next "fluxed" in weak hydrochloric acid or in a strong zinc chloride solution, partially dried and introduced into a bath of molten zinc. Fluxes, usually ammonium zinc chloride mixtures, and various mechanical devices are used to keep the surface of the zinc bath clean at the points of entry and exit. These vary, of course, with the type of material being handled. Sheets are fed by driven rolls immersed in the bath and exit between partially submerged spirally grooved rolls. Wire is pulled through guides and exits through sand, charcoal or a wad of asbestos mechanically held in contact with it. These exit rolls and "wipes" smooth the surface and remove some of the zinc. Other products than sheet and wire are handled semimechanically or by hand and may be shaken, jarred, rotated, or centrifuged (as in the case of nails and small parts), to evenly distribute the coating and remove excess zinc. In all cases the work must be properly handled until the coating has frozen in order to avoid marking and to secure as even a distribution as possible. The appearance may be controlled by the use of cooling air, the application of SO₂ or ammonium chloride to the still molten coating and by local chilling to start crystallization and control spangle pattern.

Variations to every step described above have been proposed and many are in use. For example, cleaning may be accomplished by oxidation and reduction of the surface. Fluxes can be eliminated if the material, its surface free from oxide, is introduced through an inert or reducing atmosphere. The character of the alloy layers (see below) and of the coating may be varied by varying the composition of the steel surface through carburizing, phosphorizing, and other surface treatments, or through the addition of alloying elements to the zinc bath.

In the hot dip method the zinc alloys with the iron forming one or sometimes two layers of definite iron-zinc alloys between the steel base and the outer layer of substantially pure zinc. The character and thickness of these alloys are dependent on many factors in the process: The temperature of the zinc bath, the time of immersion, the composition of the steel, the condition of the surface. The adherence of the coating when bent is affected by the alloy layers, a thin, even alloy layer being most desirable.

Hot dip coatings consisting entirely of iron-zinc alloys are produced on sheet and wire either by very tight "wiping" of the work (see below) or by subsequent heat treatment which causes all of the zinc to alloy with the iron. Such coatings when bent, crack in an infinite number of very fine cracks with some dusting of the coating. The resulting appearance of the bend is more desirable than the flaking which sometimes occurs when ordinary heavy coatings are bent but unless the flaking is very severe the life remains proportional to the thickness of the original coating, regardless of flaking or bending, because of the electrolytic nature of the protection.

The purity of the zinc used in hot galvanizing has an effect on the bending properties of the coatings. Of the common impurities found in zinc, cadmium alone seems to be important. Its presence adversely affects the bending properties of the coatings by embrittling the outer layer of zinc. Aside from this effect, the grade of zinc used has no known effect on the properties of the coating. Difficulties are encountered with most methods of sheet galvanizing when using high purity zinc and for this, as well as economic reasons, nearly all sheet galvanizing is done with "Prime Western" and other of the less pure grades of zinc. High purity zinc is used in producing high quality galvanized wire where the coating must be heavy and must not flake when bent in a splice.

Tin, to the extent of 1 or 2%, is frequently added in sheet and hardware galvanizing to control the spangle, that is, the crystalline appearance of the surface. Aluminum is also added in very small fractions of a per cent in "hand dip" galvanizing (other than sheet and wire) to improve brightness.

The thickness of the coating applied by hot dipping depends on the time of immersion (which controls the thickness of alloy), the speed of withdrawal from the bath (which controls the amount of zinc adhering) the temperature of the bath (which affects both), and on the amount of zinc removed by wiping, jarring, or centrifuging. In the case of sheets the depth of metal above the line of contact of the exit rolls is an important factor. In general, it may be stated that heavy coatings may be more cheaply applied by hot dipping than by any other method but that their adherence when bent may be inferior to electrodeposited coatings.

The electrogalvanizing method of zinc coating is simply a zinc electroplating process. In the past, thin dull coatings have been produced at low rates of deposition. Modern practice has departed from this in two major directions: One, the rapid application of heavy coatings and two, the production of relatively thin decorative coatings of high luster and brightness.

In both cases, as in other electroplating operations, cleaning of the surface is of major importance and a considerable part of modern development in the art, particularly in the field of rapid deposition, relates to cleaning. Parts supplied for bright zinc plating normally carry only a film of grease and drawing lubricant which is removed by cathodic treatment in an alkaline solution. Flat and round steel wire furnished for rapid, high current density plating frequently carries a film of rust which when removed by suitable acid treatment leaves a film of undissolved or redeposited material which must be removed prior to plating. An alternative method involving electrolytic treatment in molten caustic soda has been used commercially.

Rapid electrodeposition is attained by the use of high current densities (of the order of 200-500 amperes per sq.ft.) and pure electrolytes. The electrolyte may be a simple highly acidulated (sulphuric acid) solution of zinc sulphate or a less highly acid zinc sulphate solution containing secret addition agents to promote brighter and smoother deposits.

The replenishment of the zinc in this process is accomplished by one of two means. In one case zinc ore is leached with sulphuric acid to abstract the zinc. The resulting solution is too impure for high current density electrolysis and requires removal of the impurities prior to use. Insoluble anodes (usually of a lead alloy) are used in the electrolysis. In the less highly acid solutions zinc is supplied directly in the form of anodes of high purity zinc which are readily available. Each method has its own advantages but relatively little data on comparative costs are available.

Solutions for applying bright lustrous deposits are of the alkaline cyanide type containing various organic and inorganic ingredients to promote brightness. In one case brightness and high luster are obtained solely by maintaining the electrolyte in a state of very high purity. In all cases the zinc content is supplied by means of zinc anodes. It is a general impression in the industry that zinc of high purity is required for best results.

Electrogalvanizing is not being applied to sheet on any extensive commercial scale as yet. Electrogalvanized coatings consist of a single layer of zinc without any alloy layer. As a result, they are very adherent when bent regardless of thickness unless the cleaning has been carried out imperfectly. Electrogalvanizing offers the advantage, important in many cases, of involving no heating of the steel. Also it is claimed that greater uniformity of coating can be obtained in the case of wire but with many or most products to be galvanized this advantage cannot be expected. The appearance of electrogalvanized coatings is considered preferable in some uses. The practical range of coating thickness obtainable by electrogalvanizing is greater than by hot dipping but little information on relative costs of comparable weights of coating applied by the two methods is available.

Sherardizing which is described elsewhere in this Handbook is a third method of zinc coating which produces very uniformly distributed coatings consisting entirely of iron-zinc alloy.

Spray coating, also described elsewhere in this Handbook, should be mentioned here since it affords a means by which parts too large for treatment by any of the other methods, may be zinc coated. Like electrogalvanizing, it involves no heating of the steel.

Sprayed Metal Coatings

By R. M. Burns*

Any metal which is fusible in the oxyacetylene or oxyhydrogen flame may be sprayed. The process is particularly suitable for coating large structures, such as storage tanks, towers, dock gates, tank cars, and water turbines; it is also useful for coating articles which because of shape or accessibility are not readily coated by other methods as, for example, cooling coils, refrigerating and ventilating equipment. In the decorative field, aluminum, bronze and other metals are applied to elevator grills, castings, light posts and other miscellaneous articles of manufacture. In maintenance and repair shops metal spraying is rather widely employed to rebuild worn parts such as crankshaft bearings, camshafts, armature shafts, pistons and cylinders.

The metal spraying process is usually known as the Schoop process after the name of its inventor, M. U. Schoop, who first developed it on a commercial basis about 1910. Essentially the process consists in melting the metal which is to be deposited, atomizing the molten metal by means of an air blast, and depositing the atomized metal upon the surface to be coated. In its original development the equipment consisted in a reservoir of molten metal which together with the auxiliary parts weighed a ton. Commercial success of the process begins, however, with the development of the portable "pistol" type of equipment weighing about four pounds. In this equipment the metal to be deposited is used in the form of powder or wire. A modern process for using liquid metal has been developed to accommodate four pounds of metal previously melted in a gas heated crucible. The pistol in this case is rather heavy and the process, although limited to low melting metals, is said to be rapid in operation and to produce coatings of uniform character.¹

The powder process of metal spraying consists in heating finely divided metallic powder to its melting point by blowing it through the flame of a blow pipe and projecting the resulting spray by an air blast. The process is limited commercially to metals of low melting point and in particular to zinc which can be obtained in powder form at a reasonable cost.

The method of metal spraying of principal importance is that in which metal in the form of wire is used in a gas fired pistol. In this process, the wire is advanced into the nozzle of the pistol at a constant rate by means of an air driven turbine, the end of the wire being melted and atomized continuously as it reaches the inner part of the conical flame. The size of the wire employed depends upon the metal to be sprayed and the character of deposit which is desired. In general, wires 0.125 in. in dia. may be used for heavy duty spraying, while for ordinary deposits wires from 0.08-0.03 in. in dia. are commonly used.

In its simplest form the nozzle of the gas fired pistol consists of three concentric tubes. The wire is advanced through the central tube, the gaseous mixture through the annular space surrounding this tube while the compressed air which accomplishes the atomizing and spraying passes through the outermost annular space or tube. The gaseous mixture of either hydrogen or acetylene and oxygen is used at pressures of 15 psi., and the most suitable air pressure is 50-60 psi.

For the spray coating of small parts a number of mass coating machines have been devised. Usually these are rotating drums, into the ends of which spray guns are mounted.

The efficiency of deposition of sprayed metal coatings depends upon the process employed, the metal used and the distance of the nozzle from the surface being sprayed. For the wire pistol and the nozzle from 4-8 in. away the efficiencies of deposition are as follows: aluminum 90-85%, brass 80-75%, zinc and tin 73-87% and lead 65-60%, respectively.

An electric metal spraying would seem to have some advantages, especially with respect to portability. Much study has been devoted to this aspect of metal spraying and the practicability of the method has been demonstrated. However, the method is not used commercially as yet.

Nature and Properties of Sprayed Metal Coatings—The minute semimolten particles which comprise the spray acquire a superficial oxide coating which becomes incorporated in the coating. The particles of metal upon impinging upon the base

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metal are flattened into relatively thin scales which are rapidly chilled by the passing air blast. As the coating is built up these scales become interlocked with others preceding and following them, giving rise to a structure of rather high intrinsic tenacity. There are, however, cavities of microscopic size between the scales at numerous points with the result that the coating is somewhat porous in nature. These cavities, together with small amounts of oxide, have the effect of reducing the density of sprayed metals. In the following table there is given a comparison of the values of density obtained for sprayed metals with the accepted values for the same metals in the ordinary form.

	Density in Cast Form	Density of Sprayed Metal
Aluminum.....	2.70	2.31
Zinc.....	7.14	6.32
Tin.....	7.31	6.82
Copper.....	8.92	7.51
Lead.....	11.34	9.77
Brass.....	8.30	7.32
Bronze.....	8.76	7.77

The density of sprayed metals may be increased by working or by heat treatment. The presence of pores in sprayed coatings is not particularly objectionable in the use of metals such as zinc, the pores of which upon exposure to moist air become filled with corrosion products, thereby improving the continuity of coating. More recently² the application of varnish to sprayed nickel coatings has been advocated as a method of reducing porosity. Usually, however, coatings are applied of sufficient thickness to prevent the existence of pores which extend through the entire coating. In some cases an undercoating of another metal, as for example zinc under tin, is used to provide a thicker protective coating. In the use of sprayed metals on bearing surfaces porosity is of some advantage in absorbing lubricants and maintaining in this way an oil film, the presence of which reduces wear.

The particles of sprayed coatings are slightly work hardened and this together with the presence of oxide results in a hardness somewhat in excess of that of the same metal in the cast form. A comparison of the scratch hardness of sprayed and cast metal is as follows:

	Width of Scratch in Cast	Millimeters Sprayed Coat
Tin.....	0.08	0.056
Aluminum.....	0.06	0.044
Zinc.....	0.05	0.032
Copper.....	0.05	0.029
Brass.....	0.05	0.032
Bronze.....	0.023	0.025

The adherence of sprayed coatings to the base metal is generally of a lower order of magnitude than that obtained in other methods of application. In the absence of alloying or chemical action between the coating metal and base material it becomes essential that the surface of the latter be clean and roughened. The best results are obtained with freshly sand blasted surfaces for this treatment appears to provide angular indentations and recesses to which the sprayed coating may become anchored. Angular steel grit may be used in place of sand for the surface blasting operation. Where it is feasible to preheat the surface to be coated it is said to give improved adherence.³ This is accomplished in some designs of pistol by the attachment of gas jets. In the coating of small articles in drums it is not difficult to preheat the parts beforehand in an adjacent chamber.⁴

Protection Afforded by Sprayed Metal Coatings—In the protection of ferrous metals against corrosion, coatings of sprayed metals of somewhat greater thickness than those applied by hot dipping and electroplating methods are required to assure comparable service. It is common practice, for example, to use sprayed zinc and aluminum coatings 0.004-0.012 in. in thickness depending upon the severity of the exposure. For tin, lead and nickel coatings, metals which do not protect iron electrochemically, coating thicknesses of 0.010-0.025 in. are used. Iron and steel parts which are to be exposed to high temperatures, such as grate fingers, stacks and certain sections of the superstructures of boats are sometimes protected with sprayed aluminum coatings. In these cases from 0.006-0.010 in. of aluminum is used.

Reclamation of Worn or Undersized Parts by Metal Spraying—One of the most attractive applications, and now probably the largest field of usefulness, of metal

spraying is in building up the worn bearing surfaces of large machines.¹ Shafts of all sorts, cylinders, valves, piston rods, rolls, and axles may be readily reclaimed at a fraction of their original cost by the application of low or high carbon steels, stainless steels, or of nonferrous metals and alloys, such as copper, nickel, bronzes, brasses and Monel metal. The most common method of applying sprayed metal to such parts is as follows:

The worn shaft is mounted usually on a lathe or rolls in order to facilitate its rotation. The surface of the shaft is prepared for spraying by first undercutting to clean up the worn areas then blasting with sand or steel grit which roughens the surface in order to secure adequate adhesion of the deposited metal. Where heavy coatings are to be applied it is the practice to cut a rough thread in the surface to be coated which may be followed with a mild sand blasting. In the spraying operation the gun may be operated by playing over the surface in the usual manner, or when the shaft can be rotated the gun is mounted in a fixed position and made to traverse the rotating shaft from end to end. Thus a deposit of uniform thickness greater than the finished size by perhaps $\frac{1}{8}$ in. is obtained over length of the shaft. Finally, the oversized shaft is ground down to the proper dimension by lathe finishing or by means of wet emery and polished with fine emery. In a similar fashion large cylinders, such as penstock valve operating cylinders in power houses, have been relined inside.

This process is equally applicable to the building-up of undersized parts, and is often employed for this purpose.

Cost of Metal Spray Coating—The cost of coating ferrous surfaces by metal spraying depends upon the prevailing cost of oxygen, acetylene, compressed air, labor, and metal, besides the cost of surface preparation. Ordinarily the blast cleaning of a plain flat surface will average from 5-10 cents per sq.ft. Based upon an assumed cost of \$2.00 per hour for operation of the spray gun and the metal wire prices prevailing in April 1936, the approximate cost of metal deposition per sq.ft. of surface for coatings 0.005 in. in thickness is as follows:²

Aluminum	\$0.10
Brass23
Cadmium63
Copper20
Lead10
Monel Metal52
Nickel56
Tin24
Zinc10

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Coloring Steel

By Dr. C. B. F. Young*

Coloring of Steel in Molten Salt Baths—Molten salt baths produce colors upon iron and steel which have been polished and cleaned, and are effective, but often the temperatures required are too high, so affect the hardness of the metal. Then too, the drag-out effect must be considered. In some types of bath this loss is so great that the bath must be abandoned because of the economic factor.

If sodium hydroxide baths are used, both of the disadvantages mentioned above are avoided as it operates at 300-400°F., and the drag-out is low. The baths should be covered so as to exclude all carbon dioxide, as this unites with the sodium hydroxide to produce sodium carbonate. However, if this is formed, it can be precipitated by the addition of unslaked lime.

A black color is produced in a solution of 400 g. of sodium hydroxide, 10 g. of potassium nitrate and 10 g. of sodium nitrate dissolved in 600 cc. of water. The solution should be used at 250-285°F. The black color appears in 15-30 min. After coloring, the object should be rinsed in hot water, dried, and immersed in hot oil.

Color Produced by Temperature—One of the oldest methods of coloring iron and steel consists of heating the material up to the desired temperature, and holding it there for a definite period. As steel is heated through a gradual range of temperatures, each degree of temperature for a given specimen of steel produces a corresponding shade, which varies from straw yellow, through brown, purple to dark blue. By properly controlling the temperature, each of these colors can be produced.

Below is a table showing the colors with their corresponding temperature. This is only general, as different steels will vary somewhat.

°F.	Color
400	Faint straw
440	Straw
475	Deep straw
520	Bronze
540	Peacock
590	Full blue
640	Light blue

The colors produced by the above method are generally not uniform due to the fluctuation of the temperature. This can be controlled much better provided the steel objects are immersed in a molten bath of lead or salt as described below.

Polished strip steel is colored straw or blue by passing it through a small lead bath at a suitable temperature and speed. The desired color develops after the steel leaves the bath and comes in contact with the air. The amount of coloring is controlled by passing the strip steel through wet waste located a short distance from where the strip emerges from the lead.

Strip steel is also satisfactorily colored by passing it through a salt bath. The coloring takes place in the bath. After leaving the bath the adhering salt must be washed off with hot water and the steel dried before winding it on the reels.

In both methods the strip steel to be colored must be thoroughly cleaned and dried, and free from oil or finger marks.

Sand may also be used as the bath. The sand may be on a hot plate, or better, in a cylinder capable of being slowly rotated and heated by a gas flame underneath. From five to ten minutes will produce a fine rich blue when the sand is at approximately 650°F.

The work may also be placed in a sheet metal box with a small amount of sand. The box and contents are agitated back and forth over a fire.

When using either method, experience will be required to know just when to remove the work from the fire. The sand is sifted out by means of a wire sieve and the work dipped into oil to set the color.

When it is desired to do tinting on a large scale, continuous sand tempering machines are often used. The work is carried through a perforated drum and

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heated sand is automatically sifted into the drum. Adjustments of the temperature and rate of feed may be so made that a continuous stream of work having a uniform color is secured.

Heat tinting may also be done on a large scale in a rotary retort without the use of sand. The tint color is controlled by the operator. He must regulate his temperature accurately and keep close watch of the work to be certain that it is removed when the desired color is secured.

For continuous simultaneous heat tinting and tempering, machines are procurable with or without sand as a part of the process. The sand serves to cushion the work to prevent battering which might result in tumbling articles of certain shapes and weights; furthermore, the heated sand insures complete diffusion of the heat throughout the mass of work and therefore greater uniformity in color.

It is important in all heat tinting that sufficient time be allowed for oxidation of the steel at the low temperatures used.

Niter Baths—Steel articles that have been polished and properly cleaned can be given a simple finish by immersing them in molten niter. A mixture of half and half sodium and potassium nitrate is melted in a cast iron or steel melting pot of shape and depth to suit the work. As rust from any sources affects the color of the work, the pot should be cleaned prior to putting in the saltpeter. The niter is melted, superheated to a temperature of about 900°F. and manganese dioxide added in the ratio of about 1 part oxide to 50 parts of niter, by volume. The manganese gives the molten salt a greenish-black tinge, and causes all suspended matter to settle to the bottom of the pot.

The addition of potassium nitrate increases the cost of the process. Potassium salts are deemed necessary when low temperature operation is desired. Potassium salts may be omitted from the bath, however, with equally good results. Sodium nitrate or Chile saltpeter is an excellent bluing medium, although higher operating temperatures are imperative.

As bluing by this process forms an iron oxide film on the work, consumption of the manganese dioxide would be expected. Replacement at the rate of 1 lb. of manganese dioxide every 3 hr. to a 300 lb. batch of saltpeter keeps the bath in condition. While it is doubtful what is the exact function of the manganese dioxide, this much has been observed; that if omitted from the pot the melt does not produce good work. Baths found upon analysis to be charged with iron oxide gave bad results, whereas no excess iron oxide was found in solution in any bath containing an excess of manganese dioxide. (Manganese dioxide has been omitted from some baths with satisfactory results.)

In a niter bath a peacock blue or temper blue can be consistently obtained in the following manner: The articles to be blued are first cleaned and polished. The higher the polish the brighter will be the blue color. A thin coating of oil is then applied and the articles immersed in the hot niter at 600-650°F. The pieces may be suspended individually on wires. Screws, nuts and other small articles may be dipped, inclosed in a wire basket. The parts are held in the niter for a few minutes, and then raised to note the depth of coloring attained. They are then replaced in the molten salt until they reach the desired color. The time required varies with the temperature and with the size of the pieces but is never over 4 or 5 min.

The reaction is nothing more than obtaining a uniformly colored oxide film, as is obtained when tempering steel to color. If left in the niter too long, say 10 min., the film produced is no longer a temper blue or a gun-metal blue, but has become a dirty gray. Preliminary cleaning in gasoline or similar solvent produces a bad finish, resulting in a mottled dirty surface. The oil carried on the surface of the parts takes fire immediately upon immersion in the hot niter, and if any moisture is present on the articles bad spattering of hot salt will occur.

After the right blue is obtained, the articles are quenched in cold, clean water to strike the color, then immersed in boiling water and finally in hot oil. Hot oil dip is necessary in treating small screws or other tiny parts, as it removes from them all moisture, which if left on the blued article will form a spot of red oxide rust, a defect which has a tendency to form at the roots of threads or any reentrant angle. A darker gun-metal blue may be obtained by using a temperature up to 1000°F.

Care should be taken not to dip articles after adding manganese dioxide to a niter bath until the suspended oxide has sunk, as otherwise dirty spots will

appear on the blued article. Cast iron, if highly polished, will take on a gun-metal blue corresponding to that given to polished steel, but it requires about 20 min. immersion at 1000°F. to accomplish this result.

Charcoal Bluing—The charcoal bluing process consists of introducing highly polished work in a bed of hot charcoal. The bed of charcoal is approximately 2 ft. deep. The lower regions of the fuel are in a state of incandescence, whereas the upper layers possess temperatures which are suitable for the development of oxide colors. After the desired shade of blue is developed the work is rubbed vigorously with waste which has been dipped in raw sperm oil.

Oil Blackening—To oil blacken, the polished steel part is packed in a carburizing box, using spent carburizing compound, and properly luted to exclude air. Box and contents are heated to 1200°F., requiring about 1½ hr. At 1200°F. the box may be drawn, the lid opened and the parts riddled free from carburizing compound and at once quenched in oil. A black oxide skin is formed, dull in appearance but uniform in texture.

A comparatively good black color can be obtained quickly by heating the work to a temperature of 1000-1200°F. and quenching into oil. The appearance of this finish depends upon the surface of the work prior to heating. This finish is not so good in color nor in lasting qualities as the gun-metal finish.

Small typewriter parts are given a black finish by heating in a rotary retort furnace to a temperature of about 750°F. After the work has reached the desired temperature, a small quantity (about 1 oz.) of linseed oil or fish oil is added to the charge in the retort. The work is revolved from 3-10 min. longer, when it is taken from the furnace and spread in pans to cool in the air. After cooling the parts are dipped in a rust retarding oil.†

To simultaneously oil blacken and temper, place the articles which have been quenched in oil from the hardening heat and while still covered with the quenching oil, in a rotary drum retort (not perforated). Heat to 500-650°F. and maintain at temperature for the proper tempering time and the finish desired. The longer the time, the deeper and more durable the black color. Allow the retort with its contents to drop below 500°F. before discharging the articles. Then to brighten the black color tumble the articles for a short time in granular cork which is slightly oily.

Gun-Metal Finish—The gun-metal finish, also known as carbonia finish, used on a majority of rifles, shotguns, and revolvers, is in addition used for finishing small parts, such as buttons, screws, pen points, buckles, pins, saw teeth, bicycle chain links, typewriter, and calculating machine parts.

Various types of black finish can be secured. These depend principally upon the finish of the part before the special treatment is given. Cold drawn or highly polished parts will take a glossy black finish. Parts made from ordinary stampings will have a somewhat duller finish, while work which has been sand blasted prior to applying this treatment will have a black matte-like finish.

While not an entirely rust preventative coating, this finish acts as a retardant to the formation of rust.

To apply the gun-metal or carbonia finish, the work is placed loosely in a retort with a small amount of charred bone and heated to 700-800°F. After the articles are thoroughly oxidized the temperature is allowed to drop to about 650°F., when a mixture of bone and 1 or 2 tablespoonfuls of carbonia oil are added. Heating is then continued for a period of several hours. When the work comes from the retort it is a dull grayish-black and by dipping in sperm oil or tumbling in oily cork a uniform black finish is secured.

If the temperatures given will temper too much, a temperature as low as 500°F. can be used, but this lower temperature requires a longer time at heat to color the articles and the color is not so lasting as the color produced at the higher heats.

Gun-metal or carbonia finish may be applied to articles which have first been nitrided, resulting in a pleasing finish resistant to rusting and retaining the surface hardness on the articles, since these coloring temperatures do not temper the nitrided articles.

When a rotary retort is used and when the work is of such a nature that the slow rotation of the retort would cause scratches or in any way mar the finish,

†Fuels and Furnaces, May, 1924, p. 464.

special fixtures may be used to hold the work in place. These fixtures are usually necessary only when large parts are to be finished.

Coslettizing, Parkerizing and Barfing—In Coslettizing, the articles, polished and cleaned, are placed in a solution of ferrous phosphate made from iron filings, about 1% of phosphoric acid and water. The solution is boiled for approximately 2 hr. This treatment yields a light gray coating to steel consisting of basic iron phosphate, which is strongly adhesive. Due to the low temperature used, the physical properties of tempered steel articles are not affected. Even fine springs retain their elasticity and magnets are unaffected.

The method called Parkerizing differs from Coslett's original method by adding an oxidizing agent and catalyzer, usually manganese oxide (MnO), to the 1-2% solution of phosphoric acid which contains ferrous phosphate. The coating produced is then a basic ferrous-ferric phosphate, the ideal coating being one containing 3 of ferrous to 1 of ferric phosphate. After coating, the articles are gray in color, and after drying are usually coated with paraffin oil to give them a deep black color. Considerable variation of color is possible by this treatment. When the articles are first placed in the bath a large quantity of hydrogen gas is liberated, and as soon as this ceases the process is completed.

Barfing renders the metallic surface rather inert by producing a coating consisting of magnetic oxide of iron. This change, reaching to an appreciable depth, gives to the surface the durability of gun-metal. The articles to be treated are cleaned and placed in an air tight oven which has a connection introducing superheated steam at 60-100 psi. When the articles are heated to a dull red heat the steam is introduced. The coating, as one would expect, is resistant to heat. These coatings can be dyed and treated with oil or wax so that their moisture resistance will increase. The natural appearance before sealing is a light bluish slate color which darkens when oil or wax coatings are applied. These coatings incidentally prevent finger marking.

Browning—There are many processes for browning steel. The matter, however, may be summarized by describing one process, in spite of numerous variations, chiefly in the composition of the browning mixture. Other variations occur in manipulation and in the atmospheric conditions, artificial or natural. The longer browning processes have relatively low temperatures and humidities, while the shorter processes have relatively high temperatures and humidities. The longer processes have poor conditions, while the shorter processes have good conditions for rusting.

Procedures in Browning—The articles are first thoroughly cleaned which may be accomplished by boiling for fifteen minutes in a soda solution. Any grease appearing on the surface of such a solution indicates need of soda ash addition. Then dry the parts by placing them on a draining rack. When cooled to approximately 120°F. coat with the browning solution. Apply the browning solution evenly over the surface of the article with a brush, a sponge, or by dipping. Dry for approximately 30 min., apply a second coat of the solution and dry for 30 min. more.

The articles are then placed in a warming room or cabinet, and brought to temperature, which may vary from 140°F. up to as high as 175°F. Dry heat is satisfactory, as it is its function merely to bring the article up to a temperature such that when it is placed in the humid rusting cabinet, dew will not form on the surface, causing spots in the color.

The time in the warming room will naturally vary according to the size of the pieces. Transfer them from the warming room to the rusting room. This must be at the same temperature as that of the warming room (175°F.). Humidity up to the saturation point is desired, but danger of condensation should be avoided, as pitted and spotted work will result if the dew point is reached. Articles are rusted in approximately 1 hr. and 30 min. for such shapes as bayonets, others taking shorter or longer periods, depending on the size and surface.

The rusted metal, now a dirty greenish red, is removed from the humid room to a third cabinet or room, although it is not absolutely necessary. The conditions are the same as the first room. Its object is to set the rust. The rusted metal is allowed to remain in this room for 30 min. Then the article is placed in clean, boiling water for 15 min. The articles are allowed to drain dry, and then are carded on a wire brush or fiber wheel, which removes any loose particles of oxide on the surface. This operation completes the first coating.

After the first coat, three more rustings are applied in substantially the same manner, after which the browned surfaces are given a coating of thin white slushing

All the rooms should have proper thermometer and thermostatic controls, and the rusting room a recording hygrometer. Temperature and moisture should be automatically controlled. The layout of the apparatus should permit a proper flow of work from one process to the other.

The compositions of Browning solutions are given in Table I.

Table I
Compositions of Browning Solutions

Solution	1	2	3	4	5	6	7	8	9	10	11	12	13
Ferrous chloride..... FeCl_2									0.9				
Ferric chloride..... Fe_2Cl_3	3.9	2.8	8.9	2.1	2.8	7.0			5.3	2.8	3.3	22.2	
Mercuric chloride... HgCl_2	1.2			0.7			3.3	4.5					10.0
Cupric chloride..... CuCl_2						0.5	1.7						5.0
Antimony chloride... SbCl_3												22.2	
Bismuth chloride... BiCl_3							1.7						5.0
Hydrochloric acid..... HCl						7.5	9.9						30.0
Ferrous sulphate..... FeSO_4		1.5											
Cupric sulphate..... CuSO_4	0.6			0.7	1.5				1.8		2.5		
Nitric acid..... HNO_3	1.8	8.5		6.4	8.5	4.3			2.2	0.5	3.7		
Spirits of niter.....	6.2										4.1		
Ammonium chloride... NH_4Cl								4.5					
Alcohol..... $\text{C}_2\text{H}_5\text{OH}$	4.0	3.2	40.1	2.4	3.2	78.2			2.6	1.4	3.7		25.0
Gallic acid..... $\text{C}_7\text{H}_5\text{O}_3$												11.1	
Iron filings..... Fe						2.5							
Water..... H_2O	82.3	84.0	51.0	87.7	84.0		83.4	91.0	88.1	94.4	82.7	44.5	25.0
Approximate cost per gal...	\$0.90	\$0.27	\$1.45	\$0.35	\$0.30	\$3.38	\$0.86						

Electrolytic Coloring—When iron and steel are covered with an electrolytic coat of another metal or alloy, it is not thought of as coloring but as protecting the base metal. Thus, iron and steel are colored yellow by depositing thereon a brass; red by depositing copper; black by depositing black nickel; and white by depositing a nickel-cobalt alloy. See page 1096 for composition of baths for electrodeposition of metals.

Aside from the deposition of metals and alloys, the deposition of colors by the aid of an electric current is producing good results; examples are as follows:

Blue on Iron—A good blue can be produced on iron by first depositing on this material a thin coating of electrolytic copper, using either the sulphate or cyanide bath. The copper coated steel is then made the cathode in a solution containing 1.25 oz. per gal. cupric acetate and, 0.50 oz. per gal. of gelatin. Pass through this solution a current of 1.5-4.0 amperes per sq.ft., using copper as the anode. After depositing the copper from this solution for about 15-20 min. the cathode is washed in water and immersed for 5 min. in a 5% cupric acetate solution. Hues of startling intensity are produced, one after another in succession, until finally a deep blue develops.

Color Plating—The colors produced have a metallic lustre, are free from dyes or pigments and are light fast. Practically all the colors of the spectrum from violet to red are produced in a single bath. The colors obtained depend on the thickness of the deposit and this in turn depends on the plating time, which may vary from one minute to thirty minutes or more.

The bath is composed of complex organic compounds. The work is made cathode while copper is used as the anode. The current density is approximately 0.5 ampere per sq. ft. with about 0.4 volt.

The finish of the base metal determines its appearance after color plating. Thus an article which is highly polished before color plating has a similar polished appearance after color plating. After the color plating a clear lacquer is applied which increases the resistance of the finish to wear and corrosion.

Molybdate Method—If iron or steel is made the cathode in a bath containing 7-14 oz. per gal. of ammonium molybdate with enough ammonium hydroxide to produce a clear solution, and 1-10 amperes per sq. ft. passed through the cell, various colors and hues can be obtained. The colors change several times in a cycle. When a cycle is complete, the colors are reproduced in a somewhat darker shade. If allowed to continue, black deposits are finally produced, although most of these have the disadvantage of being brittle. This bath, with modifications, can be used for coloring various metals, including aluminum.

Cleaning of Metals

By Dr. Walter R. Meyer*

Introduction—Three general methods for cleaning metals contaminated with oil, grease, or buffing compounds are in use and will be considered separately although the methods may be used individually or in conjunction with one another depending upon the material to be cleaned and the effects desired. Cleaning previous to plating, for example, should be complete, and the work should show no "water break" (on removal from water, the work should be covered by a continuous water film) whereas the requirements for cleaning previous to japanning or enameling are not so rigid. The three types of cleaning which will be considered are as follows: (a) Vapor Degreasing; (b) Emulsifiable Solvent Cleaning; and (c) Aqueous Alkaline Cleaning.

Vapor Degreasing—The vapor degreaser may be likened to the chemist's reflux condenser. A noninflammable solvent, such as trichlorethylene, is heated to boiling electrically or by steam coils in a chamber around the top of which is provided cooling coils or compartments to recondense the hot vapors, preventing the solvent from escaping. The work to be cleaned is hung in the hot vapor which condenses upon the work and washes off the grease and oil. Because the oils removed are only slightly volatile at the operating temperature of the degreaser, the hot vapor will be essentially that of clean solvent although the liquid solvent itself may be badly contaminated. The volume of solvent condensing upon the work to be cleaned and consequently the effectiveness of cleaning, is determined by the weight of the metal, its specific heat, the temperature rise necessary to bring the work to the temperature of the solvent, and the latent heat of condensation of the solvent. For a given metal and cleaner, the amount of vapor condensed will be dependent upon the weight of the metal to be cleaned. It is obvious, therefore, that light metal sections with heavy films of oil will be cleaned poorly, whereas heavy metal with comparatively heavy grease films may be effectively cleaned. The vapor cleaner has the second disadvantage of not being able to completely remove solid dirt from the surface, and frequently the work may be well cleaned of oil, but a cloud of solid dirt may adhere to the work, necessitating a subsequent wiping operation.

To overcome the difficulties mentioned, spray cleaning, combinations of two solvents or a sequence of boiling liquid, cold liquid, and hot vapor may be employed. In the last named sequence, the work is first immersed in the boiling solvent where most of the solid dirt and oil are removed. This cleaner soon becomes contaminated, but the cleaning efficiency of the system is not seriously affected. The work is transferred from the chamber containing the hot solvent to a chamber containing relatively cleaner cold solvent which is formed by the condensation of the vapor from the first cleaner. In this chamber, the work is cleaned of dirt which was not removed in the first chamber, and the solvent in this chamber is kept relatively clean by the constant condensation of the clean hot vapor and the run-off of excess condensate into the first compartment. The work is withdrawn from the cold chamber and held above the hot compartment where the hot clean vapor condenses and removes any residues of oil not removed in the cold chamber. This sequence although requiring more labor for cleaning than the simple vapor cleaning, has proved itself in practice, and allows thin, badly contaminated work to be successfully cleaned.

It is essential in designing vapor degreasers that sufficient heating capacity be provided, otherwise the vapor line in the cleaner will drop too low when the cold work is immersed and the cleaning process will be seriously retarded. Improper height of the vapor column and poor condensing facilities permit large solvent losses and lower the amount of heat which can be applied to the boiling solvent. The equipment should be designed for the required size and volume of work as closely as possible, because too large units allow higher ratios of solvent lost by diffusion to amount of work cleaned, and too small units will permit large solvent losses by displacement of vapor by the work when it is immersed.

Vapor degreasing has several specific advantages: (1) The drying of the work after cleaning is rapid which is of particular value for recessed work or where water stains might be objectionable, and (2) the high temperature of operation

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softens the solid fats and lowers the viscosities of the oils, allowing rapid penetration and removal of material in holes or crevices, (this removal would be difficult with alkaline aqueous cleaners) and, (3) metals such as aluminum or zinc which are attacked by the alkaline cleaners may be cleaned by vapor degreasing with almost no visible effect upon the finish. The installations may be made automatic and are cleaner than alkaline cleaning methods. Vapor degreasing has found particular value for cleaning of metal previous to lacquering, japanning, enameling, and general organic finishing, but must be followed in cleaning previous to plating by an alkaline cleaner to remove traces of organic matter which remain on the surface after degreasing.

The disadvantages of vapor degreasing are (1) increased cost of materials over alkaline cleaning; (2) difficulty in removing solid dirt; (3) toxicity of the solvent (this may be troublesome in poorly designed equipment); and (4) the need for subsequent alkaline cleaning preceding plating operations.

Emulsifiable Solvent Cleaning—The removal of smut from cold rolled steel, and the general removal of solid particles and oil from both ferrous and nonferrous metals has been a difficult problem. The use of emulsifiable solvent cleaners has proved effective in solving cleaning problems of this type. Emulsifiable solvent cleaners are miscible with oils and can be washed off with water although a slight film of oil may remain upon the work and necessitate a subsequent alkaline cleaning treatment before electroplating. The cleaners may be of two general types. One class is composed of a hydrocarbon-soluble emulsifying agent such as sulphonated corn or castor oil, acid sludges, or triethanolamine oleate added to an organic solvent such as high flash naphtha or kerosene. The second class is made by "blending" a soap such as potassium oleate with an organic solvent such as kerosene using such blending or coupling agents as cresylic acid, butyl alcohol, cyclohexanol derivatives, or butyl cellosolve. As much as 10% water may be added to increase the ease of emulsifying.

The use of the solvent cleaner consists in immersing the work to be cleaned in the solvent cleaner where some of the oil is dissolved and each solid particle thoroughly wetted, removing the work, allowing it to drain, and then rinsing in clean running water. A second rinse in clean warm water may follow, after which the work is usually suitable for enameling or japanning. For electroplating, the work is transferred from the running rinse directly into an alkaline cleaner to remove any traces of remaining organic matter. The solvent cleaner can stand considerable contamination from oil and may be used months.

Emulsifiable solvent cleaners are particularly valuable for cleaning chemically active metals such as lead, aluminum, and zinc, since the cleaners are only slightly alkaline and do not attack these metals. The cleaners are nonexplosive and are much safer from a fire hazard standpoint than naphthas or benzine, and they do not have the toxic effects of carbon tetrachloride. However, solvent cleaners will not clean satisfactorily if the work is wet, and the cost of dragout may be prohibitive to their use for work containing wells or pockets.

Alkaline Cleaning—The mechanism of alkaline cleaning, and the composition, testing and application of alkaline cleaners will be considered briefly:

The Mechanism of Alkaline Cleaning—An exact understanding of detergent processes has, as yet, not been realized, but certain factors have been recognized which indicate in various degrees the relative detergent values. These factors are:

1. Wetting of the surface. Good wetting power of an alkaline cleaner is usually accompanied by low interfacial surface tension of the solution.

2. Penetration of the dirt layer. The rate of penetration is greatly influenced by the temperature of the solution and the interfacial surface tension.

3. Emulsification and deflocculation. Without emulsification of the oils and greases, and deflocculation or suspension of the solid dirt in the solution, penetration and wetting power would be of little value.

4. Free rinsing ability. The poor rinsing qualities of certain soaps, such as the stearate soaps, limit their use in commercial cleaning.

5. Saponification. The value of saponification in alkaline cleaning has been overestimated. Vegetable or animal fats, or fatty acids may be removed to some extent by saponification, but the bulk of metals to be cleaned is contaminated with unsaponifiable mineral oils, or insoluble soaps and dirt which cannot be saponified and are removed by the mechanisms of wetting, emulsification and deflocculation.

Composition of Alkaline Cleaners—The usual composition of the older types of cleaners was caustic soda, soda ash, trisodium phosphate and up to 5% rosin or rosin soap. Newly available alkalis and soaps have made possible the formulation

of much more efficient detergents. The first consideration is a source of alkali which is most economically furnished by caustic soda. For milder cleaners, sodium metasilicate or sodium sesquisilicate may be used to advantage. Sodium carbonate or sesquicarbonate and trisodium phosphate are not economical sources of available alkalinity calculated on an equivalent sodium oxide basis.

A constant pH or alkalinity is desired throughout the life of the cleaner and this may be controlled to some measure by the use of substances with buffered alkalinity such as sodium tetraborate, disodium phosphate, or sodium meta, sesqui, or orthosilicate depending upon the pH level desired.

Soaps as sodium resinate, sodium linoleate, or sodium oleate, and soaps from coconut, palm, whale and fish oils are essential parts of a good detergent. Soaps increase the wetting power and are the most valuable aids for emulsification. The choice of soap depends upon the conditions of service. The properties to be considered are: Solubility, optimum cleaning temperature, lather formation, stability, rinsing qualities, hydrolysis, detergent ability and cost. Rosin has been used extensively, for example, because of its low cost, good solubility, nonfoaming tendencies, and ease of rinsing. Sodium stearate, on the other hand, has found little application in alkaline metal cleaners because of its strong lather, low solubility, and poor rinsing qualities. Numerous new synthetic wetting agents have appeared within the last few years, many of which lack the ability to deflocculate and suspend dirt although possessing excellent wetting properties. The high cost of these synthetic wetting agents has limited their application in metal cleaning although they are being used to a greater extent in textile cleaning. Some of these materials are sulphates of higher fatty acids, or naphthalene sulphonated derivatives.

In summary the essential components of a good alkaline metal cleaner are (1) a source of available alkali, (2) a buffer to control the alkalinity, and (3) a soap.

Testing of Alkaline Cleaners—Laboratory test methods for determining the relative cleaning ability of various cleaners have included measurements of surface tension, measurement of the colloidal properties, washing of soiled cloths, measuring the rate of settling of carbon, and the deflocculating action against graphite. These methods are not of sufficient value to determine the relative detergent actions for commercial metal cleaning problems. An excellent beaker test of relative wetting power may be performed by making the cleaners up to the same concentration and temperature, and noting the rate of penetration into the cleaner of steel wool wet with oil. With cleaners of good wetting power, the steel wool may settle within a few seconds whereas with poor wetting power, the steel wool will float upon the surface indefinitely.

When performing factory trials on cleaners, the temperature of operation as well as concentrations must be carefully watched. Too high concentrations may actually clean more poorly than lower concentrations and it may be noted that cleaning ability does not necessarily increase with increased alkalinity. Cleaners with mild alkalies may clean more efficiently than high caustic cleaners. The cleaning trials should be continued for some time since some cleaners maintain an almost constant detergent efficiency whereas others rapidly decrease in cleaning ability because of poor buffering or too stable emulsification of the oil from improper choice of the soap used. The foaming and rinsing qualities should be noted as well as the cleaning ability.

Application of Alkaline Cleaners—For cleaning zinc, aluminum, lead, or tin, the milder alkalies such as metasilicate or trisodium phosphate are used often together with free rinsing soaps. The pH range may be from 8 to 10.5. Light duty and electro-plater cleaners range in pH from 10.5 to 12.5 and heavy duty cleaners vary in pH from 12 to 13.5. Whale or fish oil soap solutions are frequently used as soak solutions either with or without agitation to remove buffing compounds or heavy dirt previous to the use of alkaline cleaners.

Wherever possible, electrolytic cleaning should be used because the gases liberated on the work greatly speed the cleaning action. Soft metals such as lead, zinc or tin must necessarily be cleaned cathodically (object negative electrode) because they would be badly etched if cleaned anodically (object positive electrode). Steel may be cleaned either anodically or cathodically. At the cathode, a greater amount of gas is liberated than at the anode and the hydrogen has some reducing action on oxides present. Some difficulties that may be encountered are hydrogen embrittlement and plating of a smut on the work due to the deposition of iron, copper, and other metals that may accumulate in the cleaner after it is used. Reversal of the

current will not completely remove these smuts but will oxidize metals in the smut so that they will be more readily removed in the acid dip which follows. Anodic cleaning is receiving favor because of absence of embrittlement and smut deposition.

In electrocleaners, the tank should not be used as an electrode, but separate anodes of iron or nickel should be used to prevent attack upon the tank. Chlorides should be carefully avoided and the soap content should be low or else excessive foaming with danger of an explosion, may result. The current densities employed range from 10 to 100 amperes per sq. ft. with the higher current densities giving, obviously, more rapid cleaning action.

Mechanical Methods for Cleaning Metals with Alkaline Solutions

By C. S. Tompkins*

Introduction—This information pertains entirely to the methods of application of alkaline cleaning solutions for the removal of grease and oil from metal surfaces. The chemical content of the solutions and the chemical reactions have been purposely omitted, inasmuch as this is subject matter for another article.

The removal of grease and oil from metal surfaces is in many instances a costly operation, not so much from a standpoint of the chemicals used, as it is from a time and labor cost, therefore, methods of application are as important as the chemicals employed.

Cleaning solutions cannot be standardized in the strict sense of the term because of the different kinds of oils and greases that have been used either to protect the metal or for lubricating purposes.

The strength of the cleaning solution depends upon the hardness of the water in the particular locality, the method of cleaning, the kind of oil and grease to be removed, and the kind of metal to be cleaned; when solutions are used for a particular kind of work and under the same conditions, they can be made standard to accommodate that particular cleaning problem.

Where two or more installations for cleaning metals are available, steel products are usually cleaned in one system and cast iron products in the other, the cleaning solution can then be standard for that particular cleaning problem and system.

When studying the problem of cleaning metal, the following factors must be taken into consideration:

- (1) The nature of the oil or grease to be removed—that is, whether it is animal, vegetable, or mineral. Most animal and vegetable oils or greases saponify readily, while the mineral oils do not.
- (2) The kind of metal to be cleaned—that is, whether or not it will be attacked by an alkali. Brass, zinc, aluminum, and tin are easily attacked by alkalis.
- (3) The standard of cleaning required—whether between operations, before inspection, before assembling, before japanning or enameling, or before electro deposition
- (4) Methods of application of the cleaning solution.

Methods for Cleaning Metals—There are five methods of application for the cleaning solution as follows:

1. Still tank cleaning.
2. Air agitation.
3. Electric cleaning.
4. Steam and alkali spray.
5. Metal parts washing machines.

(1) *Still Tank Cleaning*—Although still tank cleaning, that is cleaning in a tank not equipped with air agitation, is the method most commonly used, it is the most impractical of all the methods. In this method a steel tank is generally used, which is heated either by gas, steam coils, or open steam jets. The temperatures of the cleaning solutions are important; for highest efficiency they should be maintained at or near the boiling point. Because a minimum amount of mechanical action is obtained in still tanks, chemical action is depended upon entirely to saponify or emulsify the grease or oil. In some plants metal, coated with heavy oil and grease which are sometimes in chunks, is put into the cleaning tank. This tends to overload the solution with muck. This objection could be overcome by using two tanks, the first as a soak to remove the heavy grease or oil and the second as the final cleaner, or by hosing off the excess grease and oil before putting the work into the cleaning solution. This is a neglected feature, but is important from the standpoint of cost and uniformity of results.

Heating the Solutions—Steam coils placed on the work side of the tank are most practical. If steam coils are placed on the bottom of the tank, dirt and other foreign substances fall to the bottom of the tank and coat the coils, forming an insulation, so that maximum heat is not obtained. By placing coils on work side of tank, the circulation from the coils will be toward the back of the tank,

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which will help to keep the top of the solution free from oil. The area of the coils should be sufficient to keep the solution at or near its boiling point.

(2) *Air Agitation in Solutions*—Open jet steam does not produce a positive agitation. Steam, as it is discharged into the solution, condenses and forms a circulation, while air when discharged into a solution forms bubbles which rise to the top to be released, and in this manner keeps the solution constantly stirred.

Fig. 1 illustrates such an installation for air agitation.

The most practical method of installing air is to have the pipe on the bottom and in the center of the tank and not on the sides. A small pipe with a valve handy for the operator is run down the back of the tank in the center to the bottom, and a straight ell is placed on the opening end, which faces the end of the tank; into this is placed a street ell opening, facing toward the opposite side of the tank (this street ell is used so that the pipe on the bottom of the tank may be raised when cleaning the tank). Into this street ell is placed a straight pipe resting on the bottom of the tank and extending to the center. A tee is attached on the end and a straight pipe extends both ways from the tee on the bottom of tank to the ends. On the ends of these pipes, two pipe caps are attached. Small holes should be drilled on both sides of these pipes to allow air to pass through. To equalize the flow of air into the solution, the holes should be graduated in distance from each other. For instance, if the first hole is 6 in. from the tee, the next holes should be 5½, 5 and 4½ in. This air discharged into the solution forms bubbles and rises to the top creating a positive agitation so that every part of the solution is kept in motion.

As illustrated in Fig. 2, hang over the steam coils a perforated plate to the bottom of which is hinged a false bottom. The cleaning solution in the small space between the perforated plate and the tank heats rapidly, and is expelled through the perforations, attached to which are baffle plates, causing the heated solution to flow upward, forming a complete circle of flow as indicated by arrows in illustration. This method of agitation is not as effective as air agitation, but is nevertheless very efficient and economical.

(3) *Electric Cleaning*—This method of cleaning is accomplished by passing a low voltage (6-12 volts) current through an alkaline solution. An evolution of oxygen is produced at the anode and an evolution of hydrogen at the cathode or work to be cleaned. It has been the custom to make a direct connection of the positive buss rod to the tank and the negative connection to the work rod.

The metal to be cleaned is hung on these work rods, using hooks long enough to allow the metal being cleaned to be immersed in the alkaline solution. It has been found much more efficient, instead of making the direct connection of the positive buss rod to the tank, to make this connection to anode rods and use sheet steel anodes, suspended in the tank. These sheet steel anodes should be nickel plated and as nickel does not deposit in an alkaline solution the anodes will remain perfectly clean at all times. This increases the amperes passing through the solution and materially increases the efficiency of this method.

The results obtained in electric cleaning tanks are uniform and thorough. The evolution of hydrogen produced by the electric current at the cathode or work has an effect of loosening the grease or oil and it is removed very quickly. In some instances the flow of current is reversed, that is, the tank is used as the cathode and the work as the anode. In this case there is an evolution of oxygen at the work. Some tanks are equipped with a double throw switch so that the current may be passed through the solution either way. This is practical,

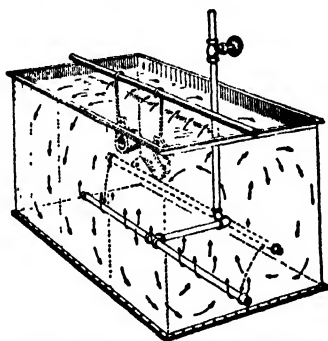


Fig. 1—Air agitation installation.

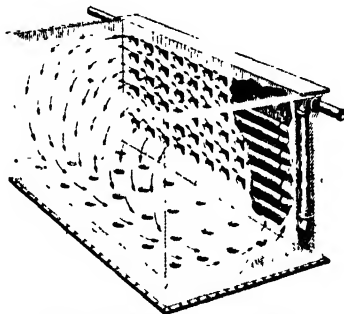


Fig. 2—Baffle plate agitation.

especially if some of the soft metals are being cleaned, such as brass or copper. After cleaning, if the flow of the current is reversed for a few seconds, it has a tendency to remove tarnish from the metal. When cleaning flat surfaces of copper and brass, 3 or 4 seconds on direct current (using the work as the cathode) and 1 or 2 seconds on reverse current (using the work as the anode) is sufficient. When cleaning die cast metal the direct current (using the work as the cathode) only should be used. Usually 3 to 5 seconds in a mild cleaner is sufficient. If work has recesses which permit of accumulations of buffing compositions, it is good practice to remove these deposits by scrubbing before placing in the electric cleaner.

Electric cleaning tanks are entirely satisfactory where an absolutely clean surface is required, as for instance the preparation of a surface for an electro deposition of metal, but it is advisable, to insure best results, to use a soak cleaner first and then rinse off so that the electric cleaner is not mucked up with heavy grease and oil.

Different densities of alkali solutions govern the conductivity and, therefore, the amperes per sq.ft. of metal cannot be stated definitely. It ranges anywhere from 15-45 amperes per sq. ft. of metal; 6-12 volts are required. In figuring square feet of surface cleaned consider both sides of the metal. In selecting anode or cathode rods or hooks, consider their ability to carry the flow of amperes without resistance. The following table is for square soft copper rod (for round copper rods deduct 25%).

Size, In.	Ampere Capacity
1 x 1	750
1/2 x 1/2	188
3/4 x 3/4	47
5/8 x 5/8	12
3/4 x 3/4	1.6

Steel or iron should never be used for hooks to suspend work in a cleaning solution.

(4) *Steam and Alkali Spray*—Garages use a direct spray of steam and alkali solution for cleaning chassis and engines. This method may also be used for cleaning parts on locomotives. With this method a double-jet nozzle is used, one side connected to a high pressure steam hose and the other feeding by gravity from a tank of hot alkaline solution. The steam and solution are mixed in the nozzle and thrown with force on the metal, cleaning the spot very quickly. This method is also used quite extensively in stripping paint from automobile bodies.

There is now an alkaline vapor employed. A small boiler equipped with coils and heated by an automatic oil burner is used. A very weak alkaline solution is mixed cold in a separate tank and is pumped to the boiler and introduced at the top; passing down toward the oil burner, it is heated and broken up, and then passes out through a hose to the nozzle where it is applied to the work to be cleaned. Pressure may be adjusted and maintained up to 170 lb.

(5) *Metal Parts Washing Machines*—Metal parts washing machines offer a very practical method of applying an alkaline cleaning solution. Small work is placed in baskets or trays and large work is placed directly on the conveyors, which carry the work through the machine where the alkaline solution is pumped through sprays and either thrown with force over the metal or splashed in large quantities over it. The cleaning action is both mechanical and chemical, and may be increased or decreased by varying the strength of the solution.

If two washing machines are used, most of the oil and grease are removed in the first machine, thereby keeping the solution in the second machine free from refuse and in the best working condition. Besides having the second solution in the best working condition, the parts have been heated in the first machine, therefore, the final cleaning is more readily accomplished. In winter it is advisable to keep the work as warm as possible before cleaning, because large parts that are cold cool the cleaning solution, resulting in lost time.

Methods Employed with Metal Parts Washing Machines—The manufacturers of metal parts washing machines employ four different methods of application as follows:

- (1) The splash
- (2) The fixed spray
- (3) The revolving wash arm
- (4) The rotary drum.

(1) *The Splash*—In the splash method, a wheel similar to a side wheel on a steamboat is revolved on one or both sides of the conveyor. In this manner, large quantities of the cleaning solution are splashed with force over the work as it passes through the machine on the conveyor.

(2) *The Fixed Spray*—In the fixed spray, pipes provided with nozzles are placed above, below, and in certain machines on both sides of the conveyor. The cleaning solution is pumped through these nozzles, the jets striking directly on the work from every angle. The stationary location of the nozzles makes it possible to use a high jet pressure, which increases the mechanical cleaning action of the solution.

(3) *The Revolving Wash Arm*—In the revolving wash, a four spoked, slotted wash arm is used, through which the cleaning solution is pumped in large quantities onto the metal to be cleaned, as it passes through on the conveyor. On the end of each arm is an adjustable nozzle and this is set at an angle so that the force of the solution pumped through it makes the arm revolve. These arms are 16-30 in. long so that the work in passing through, goes through a solid wall of swirling solution, which hits it directly from every angle.

In both the spray and revolving types of machines, the tank is below or at the side of the conveyor and is heated by steam coils. The solution is used over and over. After the solution has passed over the work, strainer pans catch the heavy foreign matter which has been washed off and by a system of baffle plates in the tank, the solution is strained and filtered so that the solution pumped over the work is always clean.

(4) *The Rotary Drum*—With the rotary drum washing machine, the work is tumbled as it passes through a perforated drum. The work is moved forward by a helical screw as the drum slowly revolves. The washing solution is forced over the work from the inside of the drum through stationary sprays.

All these machines are thoroughly practical for cleaning before japanning and enameling, and before assembling or between machining operations or for removing quenching or tempering oils, but they are not practical as a cleaning method before electro deposition.

Pickling Iron and Steel Products

By C. H. McCollam* and D. L. Warrick†

General—Pickling is the term applied to the chemical removal of surface oxides from metal by immersion in an acid solution. Wide variations are possible in the strength, temperature, and type of the acid solutions used and the procedure depends upon the material to be pickled, the character of the scale involved and the surface desired after pickling. The following discussion will deal only with the pickling of ferrous metals.

Low carbon, hot rolled steel pickling is typical of the basic principle involved. In this case the surface oxide to be removed is mill scale formed at comparatively low temperatures during or after hot rolling. Removal of such scale is one of the simplest of the cleaning problems. The material is submerged in dilute sulphuric acid until free from scale, after which it is removed and rinsed. For purposes of economy and efficiency the acid concentration is held at approximately 10% and the temperature maintained between 150 and 190°F.

A container is required in which the acid and the material to be pickled can be held for a reasonable time at the desired temperature. To this basic piece of equipment has been added such operating conveniences as cranes, temperature control instruments, and mechanical agitators. The pickling tub or tank is subject to changes in construction which will be discussed further in another part of this article, as will pickling acids, inhibitors, foam producing agents, and rinses.

Pickling Procedures for Various Ferrous Metal Products—Although pickling appears to be a simple process, numerous refinements or modifications are necessary in many instances. Because of the broad influence of sometimes obscure variables in scale formation and because of the difference in processing practice and equipment encountered even in two plants making the same product, it is not practical to reduce pickling procedure to a standard formula. In certain instances, the problem has become so complicated that even the mechanism of scale removal by pickling has become a controversial subject. Therefore, the procedures described in the following paragraphs are merely the methods which have been found to be successful in plants producing the particular material under discussion rather than formulas which can be followed without modification.

Cleaning prior to pickling is often quite as important as the operation itself. The iron or steel is frequently covered with grease from previous fabricating processes which is not soluble in acid and renders pickling difficult. Hot alkali solutions are generally satisfactory for cleaning such material, but should always be followed by careful rinsing before the material passes on to the acid. Another cleaning method is to heat the metal to a moderately high temperature for a short time to remove the grease.

When low carbon steel is pickled for enameling, galvanizing, or tinning, special precautions are necessary to insure a surface which is chemically clean as well as free from scale. A slightly but definitely etched surface is often considered an advantage in such cases because it is believed to permit greater adherence of the coating to the metal. In this case inhibitors or foaming agents can be used in the bath only with careful selection and proper precaution, since some inhibitors leave a thin but very tightly adherent surface film which clings persistently to the metal even after careful rinsing.

The trend in recent years is toward lower pickling temperatures, around 150-160°F., resulting in economy in steam consumption and in better quality of the finished product. Where time and pickling capacity permit, an acid concentration of 5 or 6% is advisable. The usual practice, however, where comparatively low temperatures are used is to compensate for decreased thermal activity by raising the acid concentration to about 10 or 15%.

In the continuous production of sheet or strip steel, provision is usually made for continuous pickling so that fabrication can proceed without interruption. In this case, control of the rate of pickling is accomplished by varying the temperature

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or the acid content of the bath, or both. Close supervision is necessary if efficiency and economy are to be realized, since the acid content of the bath is constantly changing. Acid concentration and temperature are frequently kept too high for best results in economy or quality in order that the operation may be completed in the time allowed.

In pickling for galvanizing or tinning many plants use two pickling baths: First a 5-10% solution of sulphuric acid in water at 150-190°F., and second, a short time dip in cold concentrated muriatic acid (18-20° Baumé) or in a moderately strong solution of muriatic acid at a somewhat elevated temperature. The use of high temperatures with muriatic acid is wasteful since this acid has a strong tendency to evaporate, filling the atmosphere with noxious fumes.

Vigorous mechanical agitation of the bath is always advisable. When it is allowed to remain stagnant, gas pockets tend to form which keep the acid out of contact with the metal and arrest the pickling action on these localized areas. When the steel is galvanized, these scale-retaining areas remain uncoated. Agitation offers the further advantage of securing uniform acid concentration throughout the bath, assuring a more nearly uniform rate of pickling.

When pickling sheets for galvanizing or tinning, as short a time as possible should elapse between pickling, rinsing, and coating operations. Should a delay occur between rinsing and coating the material should be stored under water and never allowed to dry. Contact of the moist iron with air will produce rusting. Furthermore, any ferrous salts from the pickling bath which dry on the work become oxidized and difficult to remove.

When pipe or seamless tubes are to be pickled, particularly those of small inside diameter, high acid concentration is advisable, since the acid solution which first enters the tube must often be relied upon to complete the pickling of the inside surface. Occasional lifting of the bundle above the bath to drain the spent acid out of the tubes helps to overcome this difficulty. Jets of air or steam directing a current of pickling solution through the tubes are sometimes a valuable aid. Mechanical rockers may also be used to advantage in the removal of thick or tight scale.

Heat treated material introduces many special pickling problems. It has been demonstrated that when alloy steels are heated above a certain critical temperature which varies with the type of steel, an electrolytic action is set up between the scale and steel during pickling. This action proceeds at the expense of the clean metal and results in serious pitting of the surface. Inhibitors have been found to be of little value in preventing such pitting. Normalizing scale represents the worst condition as far as pickling time and pickle pitting are concerned, while temper scales are the easiest to handle. Best results will usually be secured by using a fresh bath of 8-10% sulphuric acid (inhibited) with a temperature of between 145°F. and 155°F., and providing mechanical agitation.

Forging scale, like heat treat scale, is hard to remove. The scale formed at elevated temperatures is likely to be thick, glassy and extremely adherent. Scale is likely to be knocked off while handling, leaving small exposed areas of metal. At such places deep pickle pitting is likely to occur. However, when the scale is removed from large areas of metal prior to pickling the pitting is much less severe. The mechanical removal of as much of the scale as possible either before or during pickling decreases pitting. Pickling in 8-15% sulphuric acid at 150-160°F. has been found to give good results.

Pickling Stainless Steels—Stainless steels present a special pickling problem because scale containing high percentages of chromium oxides is not readily attacked by sulphuric acid alone. A common practice for stainless steels is to employ a mixture of about 10% sulphuric acid with 2-10% muriatic acid or a mixture of 10% sulphuric acid with about 10% of common salt. In the latter case, muriatic acid is generated by reaction between the sulphuric acid and the salt. Muriatic acid alone is sometimes used. In either case the pickling is followed by a bright dip in 5-50% nitric acid by volume. The more dilute solutions of this acid are generally used warm while the higher acid concentrations should be used cold because high concentrations of nitric acid are detrimental to many materials used in constructing pickle tubs. Thorough rinsing in hot water, sometimes augmented by scrubbing, is essential for best results.

Equipment—The pickling tank may be constructed of wood, steel, brick, concrete, lead, Monel metal, or stainless steel. Steel and concrete tanks are generally lined with some acid resisting material, while wood, brick, or alloy metal tanks are either lined or unlined, depending upon the service for which they are intended and the cost factor.

Wooden tanks are the cheapest to construct. They are generally made from cypress or long-leaved yellow pine. A bitumastic or similar lining of asphalt material is often used between the walls. Brick tubs, may be of common or acid proof brick, with or without mastic lining material between courses. Rubber linings may be used on wood or steel tanks. Monel metal and stainless steel offer many advantages but the cost is generally prohibitive. Steel tanks, brick sheathed and rubber lined, are satisfactory for most uses.

Acid Storage Tanks—For the storage of sulphuric acid down to 58° Baumé mild steel tanks can be used. Muriatic and hydrofluoric acid are generally stored in lead lined tanks.

Acid lines carrying concentrated sulphuric acid of 58° Baumé or higher from the storage tank to the pickle tub may be of iron pipe with iron fittings. Care should be taken to calk all the joints with a good acid resisting material. Sections of pipe which are immersed in the pickling bath should be made of lead, copper, or bronze. Heavy rubber hose is sometimes employed. Stainless steel lines are satisfactory for strong nitric acid.

When copper or bronze is used in connection with pickling equipment, there is always the possibility of electrolytic deposition of copper on the pickled surface. Ordinarily this is of no consequence, but if the stock is to be carburized without machining after pickling, the copper film will prevent carburization. Copper stains on full finished sheets are also objectionable. The use of copper or bronze in the pickling tub would be objectionable in such cases.

Drainage lines should be of vitrified tile carefully calked with an acid proof cement to avoid leakage, and should be large enough to provide adequate drainage at all times. Floors surrounding the pickle tubs should be covered with a wooden lattice, preferably of cypress.

Agitation saves time, metal, and acid. Air, steam, or mechanical movement of the tub or charge may be used, each having certain advantages. Some plants mount the tub on rockers, others support the charge on chains or saddles of acid resistant metal which impart a continuous or intermittent motion to the work. Another system involves the use of a large plunger which alternately raises and lowers the liquid level in the tub. Small articles may be pickled in a tumbling barrel. No definite recommendation can be given, for the means of securing agitation in the pickling tub will depend upon the size and kind of material being treated, the equipment available, and the character of result to be secured, thus making each installation an individual problem.

Adequate Ventilation should be provided when the pickling room is designed and should be maintained at all times. Ventilating equipment should be of acid proof material.

Pickling Solutions—Acids and acid mixtures generally used are sulphuric, muriatic, nitric, and hydrofluoric, or mixtures thereof. Sulphuric acid is the cheapest and most commonly used pickling acid. Muriatic acid is used for special purposes such as etching prior to galvanizing or tinning and sometimes for stainless steel. Nitric acid is used in the pickling of stainless steels and it is occasionally employed to oxidize scaled surfaces to facilitate pickling. Hydrofluoric acid is sometimes added to the bath to accelerate pickling, and is used occasionally in pickling castings to remove sand.

Acid Concentration—The action of the pickling solution on the metal is in approximately direct proportion to the acid concentration up to about 25% acid by weight. The concentration used depends upon the kind and temperature of acid, the type of material being pickled and surface desired. Thus when sulphuric acid is used on mild or pearlitic alloy steels the maximum concentration is 20-25% and the optimum is 8-10%. For pickling tubes and pipe a high acid content should be maintained because the solution on the inside of the tube does not circulate and consequently becomes depleted before the scale is removed if weak acid is used. Muriatic acid solution is held from 5-50% by volume. The higher concentrations of this acid cause definite etching of the surface. Nitric acid is used in amounts

of from 5-50% by volume. Concentrated solutions of nitric acid have a passivating effect on steel surfaces. The fumes from nitric acid are dangerous and adequate ventilation should be provided.

Testing of pickling solutions is an important part of pickling supervision and one that is frequently overlooked. Pickle tanks should be sampled regularly. It is a good plan to take a sample from each acid tank early in every turn. In the pickling of sheets the acid strength should be determined after each lift in batch pickling, and every 30 min. in continuous pickling. For testing the acid and iron contents a sample can be titrated with standard solutions. The use of a hydrometer for checking pickling solutions is not recommended, due to variations in gravity introduced by the ferrous sulphate content. The following procedures can be used for titrating pickle solutions.

Determination of sulphuric acid content. Measure out 5.0 ml. of pickle solution into a 200 ml. flask. Add 25 ml. of water and 2 drops of methyl orange solution. Add standard sodium carbonate solution until the last drop causes the color of the pickle solution to change from red to yellow. Each 5 ml. of the sodium carbonate solution equals 1% of sulphuric acid in the pickling tank. (This simple rule, which is sufficiently accurate for commercial purposes, is based on the specific gravity of 10% sulphuric acid.)

To make up the standard sodium carbonate solution, dissolve 11.52 g. of dried c.p. sodium carbonate in 1000 ml. of distilled water. (This standard solution is slightly stronger than N/5 sodium carbonate solution, which may be substituted without appreciable error in commercial practice.)

Methyl orange solution may be made up by adding 1 g. of methyl orange powder to 1000 ml. of distilled water. This solution should be kept in a dropping bottle.

When the pickling solution is muriatic acid the determination may be carried out in exactly the same manner as outlined above for sulphuric acid except for the final calculation. In this case each 5 ml. of the standard sodium carbonate solution equals 2.07% by volume of 20° Baumé muriatic acid or 2.36% by volume of 18° Baumé acid, each of these values being equivalent to 0.755% by weight of hydrogen chloride. (Based on the specific gravity of 10% hydrochloric acid solution.)

Determination of Iron Content—Five ml. of pickle solution is placed in a 200 ml. flask and diluted with 5 ml. of water. Standard potassium permanganate is added from a burette until the last drop turns the pickle solution to pink. Each 5 ml. of standard permanganate solution equals 1% of iron or 5% of ferrous sulphate. The pink endpoint fades quickly when organic inhibitors are present, therefore, the titration should be carried to completion as rapidly as possible.

The standard potassium permanganate solution can be made by dissolving 6.01 g. of c.p. potassium permanganate in 1000 ml. of distilled water. (This standard solution is slightly weaker than N/5 potassium permanganate, which may be substituted without appreciable error in commercial practice.)

Acid Addition—The acid content should be maintained at all times above the minimum found to be practical for the material being pickled. For mild carbon steel and most alloy steels requiring a sulphuric acid solution this would be about 5% of acid. Acid additions should be made frequently and in small amounts to hold the bath uniform. The bath should always be agitated when acid additions are made to assure thorough mixing.

If acid consumption is to be accurately established many factors must be considered. The acid addition must be carefully measured, either by metering or by means of a measuring tank. When additions are recorded as being so many "minutes of acid" through a pipe, there are generally variations due to the amount of acid in the tank, the air pressure on the acid line and other factors. Variation in the size and shape of material being pickled has considerable influence on acid consumption.

Changing of Pickle Solutions—The damping effect of ferrous sulphate on pickling bath efficiency is well known. The ferrous sulphate content of a bath is five times the iron content; and it has been demonstrated that with 40% ferrous sulphate (8% iron) the rate of attack of sulphuric acid on steel is reduced 50%. It is common practice to run the ferrous sulphate content up to 25% (5% iron), then use the solution until the acid content is reduced to less than 5% and dump the tub.

Disposal of Waste Liquor—The practice of dumping waste pickle solutions into sewers and streams has resulted in stream pollution. Legislation has been introduced in many states requiring the neutralization of pickling acid before disposal.

Recovery plants may be installed in connection with large pickling installations for recovery of acid and salvage of iron compounds. Such plants are expensive to build and maintain and consequently their application is limited. Smaller pickling plants find it more economical to kill the spent acid with lime in settling basins.

Pickling Temperatures—The heating of pickling tanks is generally accomplished by introducing live steam through an open or perforated lead pipe. Temperatures can be taken at intervals by an ordinary thermometer or indicating or recording instruments can be installed for this purpose. Temperature controls are available for installations where temperature variation must be held to a minimum.

The effect of temperature on the activity of the pickling bath is generally recognized. Sulphuric acid at 190°F. has over 100 times the solution rate of the same acid at room temperature. Overpickling is likely to occur at high temperatures. The use of an inhibitor is an important factor in establishing the limiting temperature since some inhibitors fail rapidly at high pickling temperatures.

While a temperature of 170-190°F. is sometimes satisfactory when the time cycle is short, pitting may result if the pickling period is prolonged. With many high carbon and alloy steels a pickling temperature of 140-150°F. has been found to be satisfactory for efficiency, surface quality, and inhibitor life.

Pickling Inhibitors—Definition—Pickling inhibitors are agents which may be added to an acid pickling bath to diminish the attack of the acid on the metal areas from which the scale has been removed, without appreciably retarding the rate of scale or rust removal by the acid, and to diminish the severity of hydrogen embrittlement.

Theory and Mechanism of Inhibitors—The actual mechanism of inhibitor action is not well understood. Some investigators believe that inhibitors are negative catalysts that are selective in action, retarding the reaction of acid on metal but not on scale. In practice no inhibitor continues its original effectiveness unabated throughout the entire pickling cycle. However, they lose efficiency so slowly that the loss could hardly be attributed to reactions in which the inhibitor plays a major part as reagent. The effect seems analogous to the familiar poisoning of a catalyst.

Various observers have stated that inhibitor action seems to be associated with an increase in the hydrogen overvoltage at the metal (cathode) surface. A protective coating of hydrogen is thereby maintained on the metal surface which helps to protect the metal from direct contact with the acid, thus diminishing the attack.

Another theory is that a thin layer of inhibitor material is adsorbed or plated out on the surface of the metal. Many of the known organic inhibitor solutions are colloidal in nature, which lends support to the possibility of either adsorption or cataphoretic migration of inhibitor particles. On the other hand, such a layer, if existent, is so extremely thin as to escape detection in many instances.

Nature and Composition of Inhibitors—A wide variety of materials have been advocated and used as inhibitors, from cabbage leaves or wheat bran to complex synthetic organic chemicals. In numerous instances raw materials and by-products have been found to be useful as inhibitors, and many are still being used without the separation or identification of the active ingredient. A comprehensive list of such materials would be difficult to prepare, but would include the following: Sludge acid from oil refineries, waste animal materials, waste sulphite cellulose liquor, wheat bran or off-grade flour, sulphonation products of such materials as wood tar, coal tar, and asphaltum. These materials vary widely in their effectiveness and uniformity. They have an economic advantage and are not necessarily inferior to synthetic inhibitors.

A wide range of synthetic chemicals have been reported as showing inhibitive properties. Many of these are extremely complex in structure and high in molecular weight. Aldehydes, thioaldehydes, mercaptans and other sulphur-containing organic compounds, organic nitrogen bases and their derivatives, particularly those in which the nitrogen is linked within a heterocyclic ring, such as pyridine and quinoline, seem to be favorites. Their cost often precludes their use for production

work. Some of these compounds are so efficient, however, that extremely small amounts are required.

Foaming Agents—The function of foaming agents is to blanket the surface of the pickling solution with a suds which traps and holds any fine spray of acid that would otherwise be carried into the atmosphere with the hydrogen gas evolved. Their chief advantage lies in their ability to prevent the pollution of the atmosphere with acid fumes.

Confusion still exists in the minds of many concerning the relation between inhibitors and foaming agents. Actually they represent independent phenomena, although in many preparations they are co-existent. When sufficient quantity of a good inhibitor is used the evolution of hydrogen gas is so small that the use of a foaming agent becomes practically unnecessary.

Methods of Testing Inhibitors—Because of the wide variety of inhibitors and their diversity of behavior, it is important to have some method of testing their efficiency. While the ultimate test is their behavior in the pickling bath, laboratory tests offer a convenient means of comparing the value of inhibitors under carefully controlled conditions.

Laboratory tests for inhibitors are of two general types: (1) Those which measure the loss in weight of metal in inhibited acid, and (2) those which measure the amount of hydrogen evolved. The latter test depends on the fact that when metal reacts with a nonoxidizing acid hydrogen is evolved, but when the acid reacts with metallic oxide, water is formed with no gas evolution. Hence a theoretically perfect inhibitor should allow removal of the scale with no evolution of hydrogen.

Inhibitors frequently fail in service due to localized overheating. This occurs at the point where steam is introduced into the bath. Laboratory tests should take this fact into consideration. A satisfactory check may be secured by refluxing a sample of the inhibited pickle solution for not less than 1 hr. Because of the wide difference in the acid solubilities of high and low carbon steels, inhibitor efficiency tests should be made on the same grade of steel as will be treated in the pickle tub.

Advantages and Disadvantages of Acid Inhibition:

Advantages:

1. Reduces metal loss.
2. Saves pickling acid.
3. Prevents or minimizes scrap losses resulting from overpickling.
4. Decreases blistering and hydrogen embrittlement.

Disadvantages:

1. Increased pickling time.
2. Possibility of residual surface film which may interfere with subsequent operations.
3. Added cost of inhibitor.

Washing and Liming After Pickling—The importance of a clean rinse tub is not always appreciated. Ferrous sulphate gradually accumulates in the rinse water. Traces of ferrous sulphate which remain on the steel after rinsing will oxidize upon drying, leaving a film of rust on the surface. Acid also tends to accumulate in the rinse tub and promotes rusting of the steel on exposure to the air.

Complete removal of the last traces of acid with water alone is difficult even with thorough rinsing in clean tubs. When pickled steel must be protected from rust, an alkaline rinse to remove the last traces of acid is advisable. A solution of $\frac{1}{2}\%$ of caustic soda and $\frac{1}{4}\%$ of trisodium phosphate ($\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$) in hot water is effective. The alkalinity of the bath should be checked frequently and maintained by the addition of caustic soda. Acid titration (methyl orange indicator) is the best means of determining the alkalinity. Five ml. of the above alkaline solution should require 5-10 ml. of N/10 sulphuric (or hydrochloric) acid for neutralization.

A cold dip in milk of lime is also effective for neutralizing traces of acid. This method leaves a coating of lime on the surface which is not easily removed. In pickling prior to cold drawing operations this is an advantage because the lime acts as a lubricating agent.

The presence of a white suspension of solid material is not proof that sufficient lime remains in the solution. Calcium sulphate, formed when lime reacts with sulphuric acid, is a white powder which is only slightly soluble in water, and may easily be confused with lime. Titration of the available alkali with a mineral acid gives a positive index of the lime content of the solution.

Pickling Defects—Pickling is frequently blamed for certain defects which appear during the pickling operation but which have their inception elsewhere. The tendency is to blame all failures on overpickling or to condemn the steel as being defective. Certain defects, however, are due to neither of these causes, but are the result of earlier operations such as rolling, heat treating, or forging.

Overpickling is characterized by porosity of the transverse surfaces and a roughening of the whole surface, with discoloration and decrease in size and weight. This can be avoided by removing the material from the bath promptly when pickling is complete. Inhibitors aid in preventing overpickling, but are not a complete guarantee that it will not occur.

Pickle pitting may be classified into several different types according to cause. Three of these are sufficiently common to justify special consideration.

By far the most prevalent and troublesome type of pitting, particularly on heat treated alloy steels and forgings, is electrolytic. This is characterized by a patchwork of pitted areas of irregular shapes, the depth being indirectly proportional to the area. Such pitting is due to an electrical potential between the scaled areas and clean steel, the pitting occurring only where the scale is removed from small areas prior to pickling or at an early stage in the process. It should be noted that the pitted areas frequently are longitudinally aligned. The boundaries of such pitted areas are usually rather sharply defined or channeled, probably due to maximum potential existing at such locations. However, when inhibited acid is used the pitted area is generally uniform in depth, with a channeled boundary, while in uninhibited acid the pitted area is irregular in depth.

Although it seldom occurs, severe pitting may be caused by overpickling, particularly in inhibited acid. This is indicative of carelessness on the part of the pickler because it appears only when material is allowed to remain in the bath far beyond the time necessary for complete removal of scale.

Pits which have their origin in the rolling process, due either to rolled-in scale or refractories are intensified during pickling.

Nonmetallic inclusions, segregated carbides, or surface strains are frequently held responsible for pickle pitting. While these factors may have some influence, their importance has been overstressed and it is always advisable to first investigate the causes discussed in the preceding paragraphs.

Blistering is a troublesome defect on sheet and strip steel. Of the several theories advanced concerning the origin of blisters the most reasonable seems to be that they are due to gaseous inclusions in the steel, forming gas pockets just beneath the surface upon rolling. Hydrogen generated in the pickling operation penetrates these pockets and lifts the surface, causing a blister.

Properly selected inhibitors may minimize blistering but it is doubtful that they will entirely prevent it.

Hydrogen embrittlement is a phenomenon that gives some trouble when cold working operations follow too soon after pickling. It seems to be due to the intermolecular penetration of the steel by nascent hydrogen. This type of embrittlement is not permanent and may be eliminated by aging or more rapidly by soaking the steel in boiling water. Inhibitors are valuable in minimizing this effect.

Safety—Strong acids and alkalis cause severe burns if not counteracted promptly, and are destructive to clothing. A supply of cold running water should be available at all times for washing. It is important that large amounts of water be used, for when small amounts of water are added to concentrated sulphuric acid much heat is generated which may add to the severity of the burn. Safety showers with a platform release are recommended in this connection as providing the necessary volume of water in an emergency.

To remove the last traces of acid from the skin after thorough rinsing with cold water use sodium bicarbonate or baking soda, either dry or mixed with water. In case of severe injury consult the medical department for further treatment. Ammonia may be used on clothing, but should not be used on the skin.

To remove traces of alkali left after washing with cold water use powdered boric acid or a saturated solution of boric acid in water. Consult a physician for further treatment.

Hydrofluoric acid burns are exceedingly severe and painful, hence the utmost care should be used in handling this acid to prevent any contact whatsoever with the skin. Material being pickled in this acid should never be handled without rubber gloves.

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Electrolytic Pickling of Iron and Steel

By Walter R. Meyer*

Electrolytic pickling of iron and steel has been employed for a number of years to escape some of the difficulties attendant with still pickling. The removal of rust as Fe_2O_3 is comparatively easy with still pickling methods, but the removal of the black magnetic oxide of iron, namely, Fe_3O_4 , which is slowly soluble in sulphuric acid, is a difficult problem without the use of electrolytic methods. Before discussing specific electropickling processes, some general problems such as the nature of scale and its removal, and hydrogen embrittlement will be considered.

The Nature of Fire Scale and Its Removal—The black oxidation product of iron which results after the heat treatment of iron or steel and commonly called "fire scale" or "hammer scale" is composed, according to Winterbottom and Reed,¹ of 80% FeO , 18% Fe_3O_4 , and a top layer of Fe_2O_3 . The composition of fire scale on hot rolled stock and heat treated parts may vary considerably from this analysis, but the important point to consider is that the composition of the scale varies from ferrous oxide at the metal interface to magnetic oxide with a thin layer of ferric oxide. Hering² has found that the magnetic oxide is hardly attacked by sulphuric acid, but that hydrogen either formed electrolytically or by the attack of the basis iron by the acid leads to rapid dissolution of the scale. The probable mechanism of fire scale removal is an acid attack on the ferrous and ferric oxides, partial reduction of the magnetic oxide and the dissolution of the reduction products, the reduction resulting from the electrolytically formed hydrogen or in the case of still pickling by the action of the acid on the iron, and lastly a resultant undermining of the residual scale with some mechanical lifting action provided by the discharged hydrogen.

Advantages of Electrolytic Pickling Over Still Pickling—The electrolytic pickling processes are far more rapid than still pickling, requiring in most cases from 1-3 min. for completion, whereas still pickling may require from 10-15 min. for the same type of scale. Much less acid is consumed in electropickling than still pickling the consumption being according to Thompson and Mahlman³ about 50% less for electrolytic than still pickling. The savings in iron and acid usually outweigh the added cost of power for electrolytic pickling. The scale reduction efficiency of the electrolytically formed hydrogen varies from 10-50%, being most efficient at 50°C. and at a current density of 50 amperes per sq.ft.

The attack on the base metal and in some processes the hydrogen embrittlement is much less for electrolytic pickling than with still pickling. These features are important where size tolerance must be maintained and where the ductility must not be greatly impaired. Other specific advantages will be considered with the discussion of the various processes.

Some disadvantages of electropickling are the cost of equipment for the generation of the electric current, necessity of maintaining good electrical contacts, and the need in some cases of controlled temperature and concentration of acid to a greater degree than is required with still pickling. In some cases, the acid dragout losses are much higher for electrolytic pickling as the concentration may have to be maintained above 85%, whereas still pickling is done with much more dilute acid concentrations.

Hydrogen Embrittlement—Simple cathodic pickling may result in hydrogen embrittlement either equal to or greater than that which results with still pickling, but some of the special electrolytic processes, however, may result in little embrittlement. In general, hydrogen embrittlement is greater with increasing carbon content of the steel, higher temperature of the pickling bath, higher hydrogen over voltages, and may be accelerated by traces of impurities as arsenic, mercury, or sulphur compounds. With the same amount of discharged hydrogen the strength of acid used has little effect on the embrittlement.

The original ductility of the steel may be almost completely restored by heating for 2 hr. at 100°C., 10 min. at 150°C., or by immersing in boiling water from 2-5 min. Gradual recovery may occur on standing for several days at room temperature, but in all cases of treatment the original ductility is never completely restored.

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The Madsenell Process—The Madsenell Process⁴ employs anodic electropickling to remove absorbed gases and carbon smut to secure an excellent surface for adhesion of electrodeposits or hot dipped coatings. The work is first cleaned and pickled either with the conventional still methods or electrolytically and then transferred to the Madsenell "degassing" bath. The electrolyte is sulphuric acid of concentration greater than 85% maintained from room temperature to 100°F. The work is made the anode with the current on when immersed. A 12 volt line is usually employed which provides a current density of 50 amperes per sq.ft. initially, but which drops within from 30 sec. to 10 min. to almost zero current with resultant cessation of the gas evolution.

The work has then been effectively cleaned of surface smut and has been degassed to a large measure of hydrogen which may cause embrittlement. The merit of the Madsenell Process lies in its ability to remove some of the effects of the pickling of the fire scale rather than being a method designed for the scale removal itself. Some possible disadvantages may be the necessity of maintaining a high acid concentration in the bath, the need of direct current generators or rectifiers, and the maintenance of good electrical contact.

The Hanson-Van Winkle-Munning Electrolytic Bright Dip—This process⁵ is carried out in two steps. The work is first made the cathode in a warm dilute sulphuric acid bath of from 10-20% acid at a current density from 10-150 amperes per sq. ft. for several minutes. The scale is effectively removed but the work may be coated with an "acid black". To remove this smut the work is rinsed and transferred to a stronger acid bath (40-50%) where it is made the anode for a short time employing a current density from 100-150 amperes per sq.ft. The total time required may vary from 2-5 min.

High current densities and low temperatures (50-90°F.) are favorable to the production of a good bright surface. With too low a current density or too high a temperature, the surface will be clean but not bright although higher temperatures can be offset to some extent by using higher current densities. The production of the bright surface may be due to the formation of persulphuric acid which is favored by low temperatures and high current densities. The current density referred to is the initial value as polarization sets in rapidly and the current density drops quickly with a cleaning and then a brightening of the work.

The process imparts a silvery surface free from smut and scale with only a small degree of etching and a considerable reduction in embrittlement due to the anodic treatment. The need of good electrical contacts for maintenance of high current density and the necessity for cooling the acid for the anodic treatment must be considered.

The Bullard-Dunn Descaling Process—The Bullard-Dunn Descaling Process⁶ has found extensive use in removing scale from heat treated parts without attacking the base metal. After removal of oil, the article to be descaled is made the cathode in a 10% sulphuric acid bath heated to 140-150°F. and electrolyzed at a current density of from 60-75 amperes per sq.ft. A small quantity of tin or lead is maintained in the bath which results in a deposition of a thin film of either metal as soon as a bare section of iron is exposed. The deposition of tin protects the steel from acid attack and adds "throwing power" to the cleaning process because of the high hydrogen over-voltage of tin. The current discharge is consequently directed to the section covered with scale where the hydrogen exerts both a reducing effect and a mechanical action to lift off the scale. Deep recesses, threaded parts, and irregularly shaped objects are readily descaled and coated with a thin layer of tin or lead which helps to protect the metal from subsequent corrosion and does not interfere with machining or in the case of tin, with hot galvanizing or hot tinning. For electroplating or other cases where the tin or lead must be removed, the work is made the anode in a hot solution of caustic soda and trisodium phosphate where the protective film removal is accomplished in a short time.

The use of ferrosilicon anodes such as Duriron⁷ in the descaling bath lengthens its life considerably because of their ability to prevent the formation of ferric iron, the presence of which rapidly decreases the efficiency of the bath. Iron concentrations as high as 10 oz. per gal. will not destroy the effectiveness of the bath as long as they are in the ferrous condition. A large portion of the ferrous sulphate may be removed by chilling the solution. From 1-2% of the total anode surface is block

tin to allow a constant feeding of tin to the bath to compensate for that which is plated out in the descaling process.

The operation of this process is not particularly critical as to current density or composition of solutions, scale removal is rapid, the attack on the base metal is almost negligible, and its ability to remove scale from recesses is excellent.

Pickling of High Speed Steel—High speed steels containing tungsten, chromium, and vanadium are pickled with difficulty in nonelectrolytic pickles. R. R. Rogers¹ has reported a process which involves anodic pickling at 25 amperes per sq.ft. in a bath at room temperature containing 15-16 oz. per gal. of caustic soda and 2 oz. per gal. of citric acid. The electrolysis is continued for a few minutes until a uniform evolution of gas sets in which denotes the end of the pickling process. The work is removed, rinsed, and then dipped into strong hydrochloric acid (6-12N) to remove a smut which formed in the anodic pickling.

Some high speed steels may require a preliminary anodic treatment at 60 amperes per sq.ft. in 6 N hydrochloric or sulphuric acid before subjecting them to the alkaline anodic treatment. For both high speed steels and carbon steels, anodic pickling in hydrochloric acid results in an attack upon the metal itself whereas in sulphuric acid the attack is largely upon the scale.

The Ferrolite Pickling System—The Ferrolite pickling process² utilizes alternating current for pickling in a sulphuric acid solution varying in acidity from 5-10%. Ten per cent by volume of the total acidity of the bath is made up of gluconic acid or a mixture of organic sugar acids. Graphite electrodes are used and the work is dumped in acid resisting baskets and lowered between the 2 electrodes without making actual contact with either electrode. Sixty cycle alternating current is passed through the solution and the work is completely pickled in a short time. Deeply recessed articles are readily freed of scale.

The gluconic acid serves as an agent for the solution of ferrous oxide and as a regenerative catalyst for the regeneration of the inorganic acid ions, in this case the sulphate ion. The sulphuric acid serves as a carrier of the current and to attack the oxides of iron.

Choice of Method for Pickling—No attempt has been made to select or favor any one method of pickling as it is the purpose of the Handbook to give sufficient information to allow the user to judge for himself the relative merits of each process for his own particular problem. More detailed information can be obtained from the patent owners of the processes cited below and the original literature.

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Cleaning Metals by Blast Cleaning Process

(Also Known as Sand Blasting, Grit, and Shot Blasting)

By Victor F. Stine*

Introduction—The process of blast cleaning metals is one whereby sand or metal abrasives (grit or shot) propelled by air or other means is directed at the surface to be cleaned. The method of application varies with the individual requirement. The centrifugal method has recently come into use. In this process, metal abrasive is thrown on the surface to be blast cleaned by means of a centrifugal force whereby the abrasive is thrown by a wheel at a high speed. This process is limited to metal abrasive because the sp.gr. of sand is too low for the centrifugal force to do as efficient cleaning as is possible with the much heavier metal abrasives.

Types of Air Pressure Blasts—There are two major types or principles used in air pressure blasting:

1. Direct Pressure type.
2. Induction type.
 - (a) Gravity principle.
 - (b) Suction principle.

Direct Pressure Type—In applying the direct pressure principle, the full pressure of compressed air is carried all the way to the tip of the nozzle. In order to introduce the abrasive into this high pressure line, it is necessary to provide a pressure storage tank in which a certain amount of abrasive is also under pressure. Through an orifice in the bottom of the tank, the abrasive is permitted to flow by gravity into the high pressure abrasive line (the pressure in the tank and line being equal). In actual practice, the apparatus often is more complicated by the introduction of adjustable orifices, shut-off means for the abrasive and air, and double chamber arrangement for obtaining continuous operation.

Gravity Type—The gravity method provides an overhead abrasive storage or other means of supplying abrasive by gravity to an induction type of gun, in which air is introduced through a jet which is in definite spaced relationship to a nozzle. The air rushing from the jet into the nozzle creates a partial vacuum in the space surrounding the gap between jet and nozzle. The abrasive introduced into this gap is sucked into the nozzle and there mixed with the compressed air, which accelerates the movement of each grain. At the nozzle tip, the air suddenly expands, pressure is transformed into velocity and the grains receive a last and quite effective "shove," so to speak. This principle, while not as effective as the direct pressure blast, is nevertheless frequently used owing mainly to its lower initial and maintenance costs.

Suction Type—The use of suction is similar to the use of the gravity type, and while somewhat less effective than the latter, finds even more application particularly in the design of automatic equipment for treating materials easily cleaned. An air jet and a nozzle are again in definitely spaced relationship, but contrary to the open hopper or funnel type of mixing chamber used in the gravity type outfit. These parts are enclosed in a body generally called "gun." An outlet is provided at some point with provision for attaching an abrasive hose or pipe line which leads to an abrasive feeding device, often many feet away. The partial vacuum inside the gun creates a strong suction in the abrasive line, which is sufficient to lift the abrasive entering the end of the hose or line for considerable distances. However, to lift this abrasive, energy is required which is lost for useful work. This accounts for the fact that this principle is the least effective of the three.

Blast from Blower—The medium of force in another method of blast cleaning is generated by a specially designed blower, which blows air at approximately 30,000 f.p.m. through a nozzle, into which approximately 10 times as much abrasive is fed as when using compressed air through a standard $\frac{3}{8}$ in. nozzle. Surfaces are cleaned by a scouring action. It is claimed that the power and maintenance costs are very low. The cleaning efficiency may not be so great as that of high pressure air blasting or centrifugal blasting.

Nozzles—A small, but important part of all blast cleaning equipment, is the nozzle. Nozzles are subject to wear, both at the inlet as well as at the outlet. The

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wear at the inlet is of concern because the size of the inlet controls the air and power consumption.

A new $\frac{3}{8}$ in. nozzle, for instance, permits the flow at 90 lb. pressure of about 211 cu.ft. of free air, requiring 40.5 hp. for its production. If permitted to wear at the inlet to $\frac{1}{4}$ in., the air flow increases to 288 cu.ft. or 35½%, and the power to 54.9 (also 35½%). It is, therefore, readily seen that it may prove to be bad economy to use a nozzle too long, particularly in equipment using multiple nozzles. The wear at the nozzle tip is much more rapid than at the inlet. It is caused by the expansion of the air, which carries a certain amount of abrasive with it, tending to force it against the nozzle walls. This also explains why abrasives of lighter sp.gr. will wear a nozzle faster than the heavier abrasives. Each moving abrasive particle has a certain kinetic energy, which is directly proportional to its weight or mass. If it were possible to fire from a double barrel gun during a windstorm a cork ball and a lead ball simultaneously, the cork ball would be deflected from its course much more rapidly than the lead ball. Similarly, the side thrust exerted by the expanding air acts quicker upon the lighter grains than upon the heavier ones.

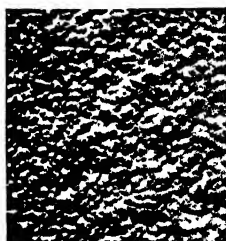
Another cause for the rapid wear upon nozzles caused by the lighter abrasives such as sand or artificial abrasives, is the fact that they travel through the nozzle faster than the heavier steel abrasives, because it is easier for the compressed air to accelerate a lighter particle than a heavier one. This higher velocity causes a larger volume of abrasive to flow in a given time, resulting in more frictional wear.

It goes without saying that granular abrasives (meaning abrasive grains which have sharp corners) cause more nozzle wear than globular grains, for example, grains of essentially spherical shape, such as metal shot. What was said about nozzle wear is also applicable to the wear of all other parts through which abrasive flows, the least wear being encountered when metal shot or grit is used. The length of the nozzle will give a more concentrated stream, whereas a short nozzle covers a larger area but shows a slightly higher abrasive velocity.

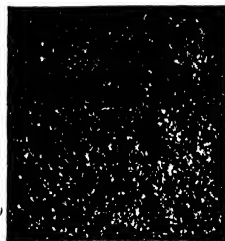
A successful attempt to reduce nozzle wear has been made with the introduction of so-called "long wear nozzles," with a tungsten carbide liner. These nozzles last about 300 hr.

There has recently been put on the market a nozzle with a liner known as boron carbide. This is said to be the hardest material made, only surpassed in hardness by the diamond.

Finishes—Almost any desired finish can be had by using the proper abrasive or mixture of abrasives. The illustrations show material cleaned with the three abrasives referred to: Metal shot, metal grit, and sand.



Shot



Grit



Sand

Surfaces cleaned with three types of abrasives.

Type and Sizes of Blast Cleaning Equipment—There are various types and sizes of blast cleaning equipment, the proper selection of which depends on the work to be cleaned and the production desired.

Air Pressure—For ferrous metals the pressure used ranges from 60 up to 100 lb., depending on the degree of cleaning required and the condition of the work. For nonferrous metals the pressure is from 10-60 lb., also depending on the nature of the work and degree of cleaning. On blast work for design or frosting effect, the air pressure is usually from 3-15 lb.

Tumbling, Rolling, and Barrel Burnishing

By Dr. R. W. Mitchell*

Introduction—Metal parts, after fabrication, often are cleaned, rinsed, rolled, and ball burnished and dried all in one sequence of operations. The words "tumbling" and "rolling" are often used synonymously. There is, however, some distinction between the two processes and the words may be used to differentiate between two operations, similar in general but differing in detail.

Tumbling, or rumbung, is an operation in which the work (usually castings or forgings) is rotated in a barrel, drum, or chest, together with stars, jacks, slugs, metal punchings, or some abrasive such as sandstone or granite chips, slag, silica, sand or pumice. Generally in this operation the work is packed tight and the barrel nearly filled.

Rolling consists in rotating a barrel containing a load of work and abrasive so that the load rolls over and over upon itself in a continuous flowing motion. Rolling may be done in either horizontal closed barrels, or in open tilt barrels. In this case the load is lighter and much more free to move within itself or "roll" as the barrel rotates. Work may be rolled with any one of a large number of abrasives of varying particle size, sharpness, and hardness, such as ground slag, sand, silice, pumice, volcanic ash, emery, carborundum, alundum, Vienna lime, crocus, rouge, and others. The abrasive is generally finer in size than is used in tumbling.

Both tumbling and rolling may be done either dry or wet, depending upon the results sought. The amount of "bite" to the abrasive, and the resultant cut, is affected considerably by the amount of water present. The water may contain dissolved chemicals such as muriatic or oxalic acid, acid salts as sal ammoniac, or cyanide, to aid in scale removal.

Ball burnishing is a method for putting a high finish or lustrous surface on metal parts, by rolling them in a revolving barrel with polished hardened steel balls (or some modification of these) and some lubricant. In tumbling and rolling, metal is removed from the surface. In ball burnishing it is not. The continuous rolling pressure and rubbing action of the heavy load of balls flowing over the metal surfaces of the work, peens and smooths out minute surface inequalities to produce the luster characteristic of an even reflecting surface. In some cases with small parts, such as buttons and rivets, the work can act as a self-burnishing load. Surface irregularities are cold worked or flowed to a more even plane. They are not cut down. Ball burnishing can be successful only on a surface properly prepared for this final finishing operation.

Tumbling might be compared to snagging or grinding, rolling is analogous to polishing or "cutting down," and burnishing corresponds to buffing. Tumbling removes sand and "skin" and scale and fins from castings, and scale from forgings. Rolling removes flash and burrs, wire edges, pits, rough spots, scale and rust, and cuts down a metal surface to an even and uniform condition. Both processes, unfortunately, also remove corners and "round-off" edges. Barrel burnishing puts a lustrous finish on a clean and smooth, but dull metal surface.

Tumbling—Foundries use a "rattler" for removing sand, rough "skin," and fins from castings. Scale and rust have long been removed by tumbling in acid, the mechanical action greatly aiding the pickling effect.

Modern tumbling equipment removes dust and dirt by exhausted air circulation and dust filters, and automatically self-loads and discharges the work as well as separates the work from the stars, sawdust and other materials.

Tumbling is the least expensive method of cleaning castings. It is claimed tumbling increases the strength of castings as the peening action during tumbling evens the surface and neutralizes internal strains. On some classes of work this has the same effect as annealing. Liberal use of stars or jacks is essential to quick and thorough cleaning to reach every pocket and corner of the castings and produce an even finish.

Barrel Rolling Operations—Rolling is done in open tilt barrels or in horizontal closed barrels. Rolling is a cutting-down operation. Depending upon time and

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abrasive the cut may be light or heavy. It is applicable to such objects as will form a rolling load in a slowly rotating barrel. Generally, this means small parts, and ones which will not entangle, nest, or interlock, which are not so thin in any cross section as to become bent, and do not require the holding of sharp edges or corners. In some cases it is possible to have a little extra metal at edges or points subject to the greatest cutting down effect, to make this method acceptable. Hollow or drilled pieces from which the rolling abrasive cannot be readily rinsed, are not suitable. Generally this process is not used for pieces having a dimension much over 6 in. An exception is long-straight work, such as curtain rods, tools, and handles, which can be rolled in a horizontal barrel in such a way that their long axes are always parallel.

The tilt barrel designed for rolling small parts has an open top and is hence readily loaded and discharged. It can be inclined at different angles for varying effect.

The rolling action increases in intensity as the axis of revolution is lowered toward the horizontal. Speed of rotation varies between 20 and 60 r.p.m. and is usually better nearer the lower figure. It should in each case be suited to the requirements of the work. The speed should never be so high as to cause the work to "throw" or move in other than a gentle rolling motion. The barrel should be loaded so as to be from 40-50% full. An advantage of the open tilt barrel is that the operator can watch the progress of the work and avoid waste of time or damage to work by over rolling.

Types of Barrel Construction—Barrels are made of wood, rubber, and most of the metals, and in a number of shapes, both round and polygonal, and with "angle-cornered" and "round-cornered" bases. These different shapes provide different rolling action. The polygonal form gives the more effective rolling carrying the load farther up the side of the barrel and allowing it to roll at a steeper slope. Barrels may be left smooth inside or fitted with cleats, fins, steps, or similar device to effect more complete movement of work in the load. The individual pieces in the load should not only roll over and over, but should rotate in more than one plane, and move back and forth slowly in direction parallel to the axis of the barrel.

Wooden barrels are used for rolling comparatively light articles either wet or dry and particularly articles of nonferrous metals such as brass and nickel silver. They are not suited to withstand the wear of rolling rough or heavy articles in sand or other coarse abrasives.

The metal of construction should be such as to avoid galvanic action with load.

Cast barrels are used for either wet or dry tumbling or rough work involving the use of abrasives as coarse sand and gravel, and on finer work requiring fine pumice or emery.

Barrels of nonferrous metal are used for tumbling articles in certain acids which would corrode iron, and for rolling high grade brass articles which might become discolored by rubbing against cast iron.

Sheet metal barrels are used to tumble heavy articles which have sharp corners that might chip out a cast barrel and rapidly wear it away.

It is usual to set up the barrels with a water pipe arranged to run into the open head. When washing and rinsing in the barrel before rolling, or in rinsing solutions after rolling, a piece of hose connected to the water line is run to the bottom of the barrel. A running, rinse then displaces the solution by overflowing.

The work is usually discharged by tilting the barrel so that the load slides into a sieve-topped box, which serves to separate work from jacks, balls, or abrasive. Stout sieve caps on metal frames which lock tight into the head of the barrel are sometimes used. In this case the barrel is lowered and run in this position for a few minutes, allowing separation of work and rolling medium. the work being temporarily retained in the barrel.

Horizontal Barrels—The horizontal type of barrel is used for larger articles, or those with one long dimension. These roll more evenly in the horizontal barrel, giving more uniform cutting down and polishing. In the tilt barrel such parts would roll end over end and produce too much action on the end faces or corners. Horizontal barrels are also structurally better suited for large and heavy loads. The horizontal barrel is more generally used for "rough work"—grinding and smoothing up—and the tilt barrel for light finishing.

Horizontal barrels with the axis of the barrel a little out of line with the axis of rotation are used to give the most effective motion to the load.

Horizontal barrels are made with one or multiple compartments. They are usually of metal, often cast iron, although other metals may be used to meet special requirements. They may be lined with wood for rolling soft or easily discolored metals. Barrels should be designed to balance and run without jerks.

When work is wet tumbled in closed barrels, the barrels must be vented every few hours as dangerously high gas pressure builds up. Finely divided metal reacts with water, forming hydrogen gas, and the frictional heat generated by the mechanical working of the load builds up the pressure.

The open ended horizontal barrel is a quite different form. It is able to handle large loads and has been developed to a high degree for automatic operation. They are made to be self loading, and by means of spiral fins on the inside surface, are self discharging when the rotation is reversed. Some have a device for separating work from stars, balls, or slugs, and automatically returning the tumbling agent to the barrel.

Abrasives and Time of Rolling—Many abrasives are commonly used. Particle size, hardness, and sharpness are factors affecting the time required for rolling. Those commonly used are slag, cinders, sea sand, sharp sand, or builders' sand, pumice, limestone, and granite chips, broken glass, silex, emery, alundum, and carborundum. Pumice is a sharp but light and soft abrasive mostly used on brass and soft metals and for finish smoothing. Hard metals require hard, quick cutting abrasives such as the last three mentioned.

To give a more uniform action, to add weight, or to carry the abrasive with a rubbing motion into depressions or corners, an auxiliary load is often added, such as wood blocks, jacks, slugs, punchings, steel balls, or steel wool.

Where the surface of the work is soft, or where a brightening action is desired rather than a cutting down, milder or finer abrasives are used. Silica, chalk, lime, crocus, polyroth, and rouge, are suitable. Leather scrap or meal, felt, and hardwood (maple, boxwood, or *lignum-vitae*) sawdust are also used, usually dry, and sometimes with fine abrasive mixed with them. Sawdust is used to follow an abrasive roll to scour fine abrasive from the metal surface. Greater cutting action is obtained in the wet process. The amount of water present has a great effect upon the process. For maximum action, the amount should be just sufficient to make a wet paste or mud. If too dry the abrasive will stick to and coat the work and barrel interior, preventing the desired action. If too much water is present, the abrasive particles are largely at the bottom of the load and do not work evenly through the rolling mass.

Water evaporates during rolling and must be replaced or the abrasive will pack and ball up. To the water may be added chemicals. Dilute sulphuric or muriatic acid, or ammonium chloride aid in removing scale. Alkali and cyanide in small amounts are often added in rolling steel to improve the color. Cream of tartar or cyanide improves the color of copper alloys. Soap solutions are not used in cutting down or polishing operations, but later in the burnishing.

Proper barrel speed should carry the load of work and abrasive up the side of the barrel to approximately three-fourths of its inside diameter. The mass should then have a slope which causes the top of the load to fall over and roll backward upon itself.

Oil is also used for rolling with sharp abrasives; kerosene is often used with emery.

Dry rolling, using sawdust, is used in preference to wet rolling for brightening up screw machine products. Fine sawdust should be used to avoid as much as possible the clogging of threads and slots. The dry roll gives a better color in the allowable time and has less injurious effect upon the threads. If sufficient sawdust is used (several times the volume of the work load) to keep the screws or bolts well spaced apart, and away from the barrel surface, they may be rolled up to 2 hr. without appreciable dulling of thread edges. This is sufficient to give a high finish. If the work has any oil upon it, a short sawdust roll of about 15 min. should be given to clean, and the sawdust then changed. It is not possible to bring the work out entirely free from sawdust, but in some cases this is not essential.

To get "high finishes" that is, smooth, even, and bright surfaces, a long rolling is required. Starting with a coarse abrasive, this is gradually broken down so that as rolling proceeds, the cut becomes finer and finer.

The length of time required obviously depends upon the quality of surface desired, and upon the condition, shape and hardness of the metal surface. The softer a metal the faster it is cut down.

Average times would be: Brass and bronze castings rolled 10-15 hr.; malleable iron castings 30-40 hr.; grey iron castings 70-80-hr. For stampings, or automatic screw machine parts, the necessary time varies greatly (from 1-100 hr.), depending upon the quality of the stock and the extent of die marks, scoring, or rough edges, brought from the machine operations. Ordinarily in preparing hot rolled and pickled stock for ball burnishing, the parts are rolled for about 48 hr. Forging scale is often removed to an extent of 80-90% by a roll of a few hours. A very much longer time would be required to completely remove it.

Often before barrel rolling and burnishing much time is saved and a net economy effected by giving one wheel operation. Sprues, parting fins, or any gross surface irregularities should always be removed by an abrasive wheel or belt. Deep scratches or score marks are also best polished out on a wheel before rolling.

Barrel Burnishing—The purpose of barrel burnishing is to develop high luster on parts otherwise unfinishable (because of size or shape), or to provide this finish at a lower cost than possible with hand labor. It allows the finishing of small parts in bulk. It can replace buffing upon a wheel in many cases. Barrel burnishing may be used as a preliminary to electroplating and as a finishing process afterward.

Burnishing has no cutting or abrading action; it must avoid these. In burnishing, rubbing pressure flattens and spreads all minute surface irregularities to a perfectly even surface. This action also tends to eliminate porosity in plated surfaces.

Burnishing will not remove visible surface irregularities, scratches, or pits. It will not improve color. These conditions must be cared for by treatment preceding the burnishing operation. (See Barrel Rolling.)

In barrel burnishing, the rubbing action which produces the burnishing may be between pieces of the work itself (self-burnishing), or between hardened steel balls (ball burnishing), or other suitable forms as cones, slugs, or pins, and the work. The rubbing pressure varies with the weight and depth of the load, and is influenced by the speed of rotation. A lubricant solution to prevent metal to metal contact in the rubbing is used. This prevents abrasion of the metal surface and heating of the load, and promotes the development of the high luster which is the object of the process.

The general rule for the ratio between amount of work and amount of burnishing agent seems to be to use about two volumes of burnishing agent (balls, et cetera) to one of work. On some work 1-1 suffices. The proper ratio is influenced by the type of barrel, and whether it is run full or only partially full, and by the form of the work. It is largely the weight of the burnishing mass which provides the pressure. It is essential that there be ample balls to completely space off and surround each piece of work. Hollow or recessed work requires a larger proportion than solid articles. Stampings require more balls than castings or forgings. One certain rule is that it is better to use too many balls than too few.

Work floating or riding upon the burnishing mass can obviously be under no pressure and hence does not burnish. Work cannot float upon the balls if there is no free space left above the burnishing load.

Burnishing Agent—Round steel balls are the most satisfactory burnishing agent generally because they can be hardened and they best supply the fundamental combination of half rubbing and half rolling action. Pressure is a necessary factor in burnishing. Too much pressure, however, between ball and work might result in grooving, or rubbing off metal. When undue pressure, because of some resistance in the load, might occur, grooving is avoided by the natural tendency of the ball to roll. The balls need not be perfectly spherical but they must be hard, smooth, and too tough to fracture.

A ball will not burnish in corners and angles. It cannot enter an angle, slot or indentation smaller than its own diameter. In such cases, or where the surface

of the work is figured, the use of other shaped pieces is required. Slugs or diagonals or burnishing steels, cones, ball-cones, fin-balls, pins or "oats" as illustrated in Fig. 1 burnish into angles, corners or grooves not reached by balls. These forms are generally used in admixtures with balls. Too high a ratio of pins or "oats" may cause a stippling effect upon flat work. When balls are mentioned, it should be understood to mean either balls, some of the modified forms, or mixtures of these.

The size unit of burnishing agent is important. Small balls obviously provide more contacts with the work. While the small balls provide more contacts, they give lighter pressure. Large balls are less expensive, and least readily lost while handling. It is common practice to mix two sizes of balls.

With drilled, slotted, or recessed work it is advisable to choose balls larger than the holes or slots into which they might otherwise wedge.

On soft metals small balls are necessary to avoid too much rubbing pressure. Balls $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ in. in dia. are the sizes most commonly used.

Much time and work are expended to make the surface of burnishing balls

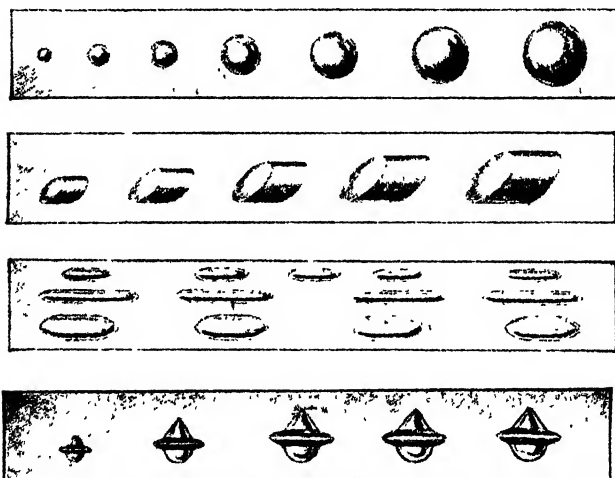


Fig. 1.—Burnishing balls, slugs, pins, and ball cones for burnishing operations (Hartford Steel Ball Co.).

work or it may be an accretion of the sticky insoluble lime soaps formed from the burnishing soap and the small amount of hardness usually present in all waters. Balls should be kept clean and bright at all times. Dirty balls are usually cleaned by rolling them with a warm solution of sodium cyanide of about 1 oz. per gal. concentration. They may also be cleaned by rolling with metal cleaner and thoroughly rinsing afterward.

Surfaces to Be Burnished—Preparatory to burnishing, the metal surface must be put in proper condition to attain the final quality of finish desired. It must be remembered that burnishing will not remove metal or take out surface blemishes. It is absolutely impossible to secure good results without a good surface to begin with; if not naturally present, it must be prepared by rolling with abrasive.

In addition to being smooth, the work must be clean of all dirt, rust, scale, or tarnish.

Burnishing will improve luster. It will not improve color. Brass and copper, bronze and nickel-silver, are often bright dipped and thoroughly rinsed before burnishing to give good color. Annealed drawn brass, or brass which through handling or standing around has taken on an uneven color, or perhaps actual tarnish, must be either bright or cyanide dipped. A dip commonly used is made up by pouring 3 volumes of sulphuric acid (1.84 sp.gr.) into 3 volumes of water. Then add 1 volume nitric acid (sp.gr. 1.4).

A pinch of salt (sodium chloride) or about 1% of hydrochloric acid (conc.)

mirror smooth. Successful burnishing with them depends upon their being kept this way. Steel ordinarily rusts easily, and balls with surfaces so roughened or pitted are seriously impaired. Steel does not rust when kept immersed in a solution of pH 9.5 or greater. A dilute soap solution, or a dilute solution of soda or alkali will have a pH of at least 9.5, and hence steel balls kept under such solutions are protected.

Balls pick up dirt or scum and become dull or even black. This may be dirt brought in on the

added daily makes the dip more effective. The temperature of the dip should not rise over 95°F. Lampblack is usually added to bright dips sufficient to form a thin covering film on the surface.

Aluminum and particularly aluminum die castings are generally first dipped in hot dilute (about 3-4% conc.) caustic soda solution for 5-10 sec., rinsed, and then bright dipped in a solution made by mixing 3 volumes nitric acid (sp.gr. 1.4) and 1 volume hydrofluoric acid (48%) used at room temperature. A container for this solution is a matter of some difficulty. A lead lined vessel, painted inside with a mixture of 1 part beeswax and 4 parts paraffin is recommended.

Hydrochloric acid (20° Baumé or sp.gr. 1.16) is used for brightening steel or iron and for removing rust. Acid ammonium citrate in dilute warm solution will remove light rust without roughening a polished steel surface.

Sometimes, after burnishing a short time a dark scum will be noticeable on the solution covering the load. If this occurs, the solution should be run out, the load rinsed, and fresh water and burnishing lubricant added.

The load of work and balls is usually just covered with water. The burnishing lubricant is added and the barrel closed and set in rotation. Of burnishing soap, sufficient should be used to build and hold a heavy cushion of suds in the barrel throughout the run.

Importance of Hardness—The harder the metal surface of the work the higher the finish it will take. Many small steel parts which are finished by ball burnishing are hardened especially for this reason. It takes longer to develop luster on the hardened metal but higher quality and more permanent results are obtainable.

Soft metals, however, can be ball burnished to a good luster. By using small balls and low speeds to avoid undue pressure, even die castings can be brought to a high finish. Brass and soft nickel plate and nickel-silver can be given a beautiful luster. Die castings on account of being soft must be ball burnished with a relatively small burnishing ball, at a low speed, and with more than the ordinary amount of lubrication.

Ball burnishing is of course just as applicable to a plated surface as to a solid metal. A hard plate will take on a better luster than a soft electrodeposit.

Zinc and aluminum die castings can usually be brought to a good finish in about 60 min. Sometimes overburnishing is detrimental. A 60 min. burnishing period is also usually sufficient for nickel or for brass.

On steel burnishing time varies greatly depending upon the quality of the surface, the result desired, and above all on the hardness of the steel. It ranges from 15 min. to 100 hr. or more.

Chromium plate is harder than nickel plate and under similar conditions should be burnished about twice as long.

Chromium solutions have what is known as a "bright range." Sometimes parts will be dark or "burned" in some spots due to too high local current density and will be dull in other parts, due to too low local current density. Ball burnishing evens up the finish by giving a more uniform brightness in such cases.

Speed and Time for Burnishing—The speed of rotation should be adapted to the nature of the work. It also depends upon the diameter of the barrel. The smaller the diameter of the barrel the faster the allowable speed. The faster the rotation the more movement in the load and the greater the number of burnishing rubs. Or on soft metals too great pressure may develop causing deformation of the surface. Small or regularly shaped pieces can be run faster than large or irregularly shaped pieces. Pieces with edges or sharp corners must be run slowly. If the work shows scratches, dents, or peen marks the speed must be reduced.

Racking and Work Holding Barrel—With pieces which scratch or dent each other, or pieces with large smooth areas which must be free from rubbing marks, racking is essential. The application of a framework into which the parts can be locked by clips, or by clamping the frame together after loading is obvious. Or, some shapes can be slid upon rods with spacers between the parts. The racks are designed to just slip into an open ended barrel.

Sometimes it is important to keep parts from nesting together. This can also be done by racking. Threads, as on studs, where only the head need be finished, can

be protected by slipping over them tight fitting short pieces of elastic rubber tubing.

Unloading the Barrel—After the burnishing has proceeded for sufficient time to give the required luster the solution is run off and the load of balls and work thoroughly rinsed with clean water. Any soap film left on the work will dim the luster. With brass, or similar alloy, residual traces of soap cause rapid tarnish and loss of color. It is then necessary to separate the balls from the work and dry the latter. The customary procedure is to dump the load upon a riddle or sieve of mesh suitable for the balls to fall through to a tray or box. The upper box is arranged to slide on cleats. After the balls are riddled through its screen bottom, the upper box is removed to carry the work to a sawdust or hot air drier. The bottom box can be arranged with a bottom sloping toward the front. The balls collecting there can be returned to the barrel by a portable loading machine.

Work removed from the barrel is commonly dried by tumbling, or rubbing with clean, dry sawdust; maple or boxwood sawdust is preferred. It is sometimes passed through a hot air dryer. The latter is used for those parts which retain sawdust, as split or tubular rivets, threaded or slotted screw machine products.

Sawdust is the best drying medium where it can be used. It acts as a cushion between pieces and prevents scratching or marring. Good hardwood sawdust only is suitable. It must be dry. Moist sawdust clings to the work and is apt to leave water marks. The sawdust is kept dry by circulation through a fanning mill or by having it in a box or bin with a steam coil in the bottom. Cob meal (ground corn cobs) is an excellent alternative for sawdust.

Burnishing Lubricants—Many kinds of material have been used for burnishing solutions. Soap, soap bark, blackstrap molasses, stale beer, alkalis, alkaline cleaners, cyanide, and cream of tartar are the most important. First and foremost among these is soap; at least in amount and extent of use.

Soaps may be made "neutral," "acid," or "alkaline," depending upon whether alkali base and fatty acid are present in exact chemical equivalents or not. Small percentages of free alkali, or of free fatty acid greatly influence the properties of soap solutions. Commercial soaps often contain added filler or builder (alkaline salts or silicate), rosin, or solvents. Depending upon the method of saponification, glycerine may be either removed from or left in the soap.

Soaps in commerce vary greatly. They vary greatly in solubility, gelling power, lathering, rinsibility, alkalinity, and viscosity. The difference in properties are important in barrel burnishing.

High titer soaps give the best lubrication and burnishing action. They may not be used where good rinsing is a controlling factor; or in a tumbling machine where their solutions would gel. Lower titer soda soaps are best where rinsing is difficult because of nature of the work.

For nickel, brass or other copper alloys, or aluminum, a neutral soap is required. A small amount of borax or bicarbonate of soda (which are less alkaline than soap) or of cream of tartar is used with the soap. On aluminum the proper nonalkaline soap means the difference between success and complete failure.

For steel, the presence of free alkali is desirable. The use of cyanide with soap upon steel is also desirable, as it increases the speed of burnishing and keeps the color white and free from a dull or leaden appearance.

The use of rosined soaps, or those containing silicate, should be avoided.

Where burnishing is done on a large scale, it is convenient to have a soap solution made up in a tank or barrel, and add a measure of the liquid soap to the burnishing barrel instead of throwing in dry soap. In this way it gets to work immediately the barrel is started. Where other ingredients are used with soap, this is particularly desirable.

The soap or soap mixture should be added in amount sufficient to build and maintain a heavy suds in the barrel throughout the burnishing period. More than this is wasteful. The volume of soap solution should be just sufficient to cover the load.

Soap bark is often used for burnishing brass and other copper alloys which are sensitive to alkaline tarnishing. Soap bark and cream of tartar, or "tartar substitute," is a favorite combination.

A good formula on steel is made by dissolving 30 lb. high titer burnishing soap in 50 gal. hot water together with 15 lb. alkali (as trisodium phosphate or soda ash) and a couple of "eggs" of sodium cyanide. This sets to a jelly soap. Use about 1 quart to average load.

Dry burnishing is sometimes done where for some particular reason the use of the wet method must be avoided. It generally takes several times as long. Steel is dry burnished with cocoa butter and lime, or sometimes chip soap and rouge; nickel with leather meal and rouge; aluminum with leather meal and whiting; zinc die castings with boric acid crystals.

After burnishing brass and rinsing thoroughly, a dilute solution of bichromate is sometimes used to hold the color. The work is then again thoroughly rinsed and dried.

Burnishing Barrels—The design and construction of burnishing barrels has developed in different directions. There are several different types all in common use. Barrels may be single or in tandem. They may be single, double, or triple compartment barrels, or a single barrel may be built with a number of different pockets, each a separate sector of the barrel. In these a number of different small lots of work can be run at one time without mixing. The barrel may rotate evenly about its axis, or with some designs, it may rotate eccentric to its axis, giving the load a combined rotational and oscillating movement.

Barrels are commonly made with cast shells. Cast iron is not good to roll articles against as it has a tendency to deaden color. Hence, these barrels are wood lined, with hard maple. It is important that a wood lined barrel be kept wet and the cover on when not in use, to prevent drying out and shrinkage of the lining. For a similar reason, wood barrels made for dry rolling should not be run wet. They will swell and buckle, or burst the bands. Wood being somewhat porous, it is essential that wood barrels be kept scrupulously clean. After use with any solution containing chemicals they should be thoroughly rinsed several times. Strongly alkaline solutions rapidly disintegrate wood linings.

Burnishing barrels are also made of cast steel without wood lining, or of iron with welded sheet steel linings. For burnishing iron or steel articles, these are more durable and provide increased burnishing area but are not recommended for brass, die castings, or similar alloys. Brass lined barrels have been used for ball burnishing brass with excellent results.

Ball Buffing—By using small amounts of very fine abrasive, such as rouge, or Vienna lime, in the burnishing barrel, the effect of buffing is obtained.

Small pellets of leather (about the size of a marble) are coated in glue, rolled in abrasive and when dry, used for dry barrel buffing on intricately shaped pieces which could not be finished on a wheel.

Slushing Compounds

By W. C. Winning*

Oils and grease-like materials employed for coating metal surfaces to protect them against atmospheric corrosion are often termed "slushing compounds". Their ability to afford complete and lasting protection is dependent upon the maintenance of a continuous and unbroken oily film which excludes air and moisture from the metal. Unlike paints and varnishes, which after application are converted by profound chemical changes to tough, durable solids, most slushing compounds are chemically inert and rely for permanence upon physical properties alone.

Slushing agents are far cheaper than paints, frequently provide superior protection, lend themselves to quick application and removal, and are of special merit where only temporary protection is sought.

Fundamental Principles—If an object has been slushed with a light mineral oil, as by dipping, it will be observed that the coating tends to thin out as the oil flows down any inclined surface. Finally the point is reached where flow ceases, yet a thin oil film remains which adheres most tenaciously to the surface of the metal. While this coating in its original form appears to afford complete protection, it gradually evaporates and when rained on, washes away to leave the metal exposed, whereupon corrosion sets in.

When higher viscosity oils are employed the thinning proceeds more slowly, the ultimate films are thicker, evaporation is retarded because of the lesser volatility of the viscous oils, and the coatings, being tougher, are more resistant to the washing action of rain. Consequently, oils of high viscosity give protection far superior to those more fluid.

The protective action of mineral oils is sometimes reinforced by additional agents which because of their chemical affinity for the metal, their low volatility, or special water resistance, add to the permanence of the oil film. An alternative procedure for enhancing the serviceability of mineral oils, lies in converting them to greases by the addition of soaps or waxes. Such greases (or slushes) if properly prepared, have no tendency to flow from inclined surfaces and consequently a protective film may be maintained of sufficient thickness to resist most, or all, weathering influences.

Methods of Application—Oils may be applied by dipping, brushing, or spraying. Often they are advantageously applied hot, the consequent lower viscosity making more uniform and thinner coating possible with resulting saving in oil consumption. Wax base slushes are best heated to above their melting point for application and may then be treated like oils. Many soap type greases, however, do not thin until heated to quite high temperatures and are then seriously impaired in quality. These are therefore usually brushed or smeared on.

As an alternative to heating, highly viscous materials may be cut back with light solvents which evaporate after application.

Before applying slushing compounds to any object, the latter should be scrupulously cleaned of all corrosive materials. Solder fluxes and grinding compounds may of themselves set up corrosion or discoloration of the metal below the slushing oil film. Finger prints may carry corrosive compounds. Perhaps the best way of removing such materials as are water soluble, is washing with an emulsion of a suitable soluble cutting oil. A thin but tenacious oil film is left on the metal surface and affords good protection until reenforced by the slushing compound subsequently applied. In some cases the soluble oil itself is sufficient protection.

Materials Used in Slushing—While in general the user of slushing compounds will best be served if he asks the assistance of the compounder, it is well for him to have a sufficient knowledge of available slushing materials to know what to seek.

Mineral Oils—These, because of their general availability and low cost, properly form the base of most slushing preparations. They may be obtained in viscosities ranging from that of water to that of asphalt and in color from white to yellow to red to black.

Those of a viscosity under 200 sec. Saybolt at 100°F. should never be employed alone unless exceptionally little protection is required. In the 200-500 viscosity

*Standard Oil Development Co., New York.

zone are the oils which give fair protection, need no heating for application, and will burn clean in heat treating operations. With oils of higher viscosity, especially of 1000 sec. and over, far more permanent protection may be obtained, though even the most viscous oils, when used alone, do not give complete protection against severe outdoor weathering.

Fatty Oils—Lard, olive, and sperm oils used by themselves give excellent protection against the atmosphere but slowly oxidize to become gummy and generate acids which, particularly on copper, brass, bronze, and solder, may seriously corrode the metal. Used in concentrations of 20% or under in mineral oils they are less objectionable, but the improvement over straight mineral oil is not sufficient to warrant their use except in special cases.

Semidrying oils such as corn and cottonseed, and drying oils such as fish and linseed, should only be used under exceptional circumstances where their gumming and acid forming tendencies are considered desirable rather than harmful.

Fats and Waxes—The addition of paraffin wax to an oil causes it to solidify. The more wax used the higher the solidification temperature or melting point. Petrolatum gives more uniform products and the resultant films are tougher and more adhesive than those obtained with paraffin wax.

Light colored petrolatums are low in melting point and adhesiveness. They should therefore be used undiluted when color requirements demand their employment. Crude heavy petrolatums give permanent films and they may be cut back with 50-80% of mineral oil to give good slushes. Mixes high in petrolatum require heating before application. High viscosity cut backs should be used where maximum durability is needed.

Fats such as lard and tallow usually offer no advantages over petrolatum and frequently introduce corrosion.

Lanolin (wool grease)—Wool grease, commonly termed degreas when crude and lanolin when purified, is considered to be free of all tendency to form corrosive acids and gums, and is characterized by a high resistance to the washing action of water and is difficult to wipe off.

The increase in free fatty acid content of lanolin does not affect its protective qualities to the same extent as does the same increase in acidity found in other products when exposed to light and air. Generally, the lanolin is carried in a light petroleum solvent which upon evaporation deposits a thin coat of lanolin on the parts to be protected. It may also be used with mineral oils, alone, or hardened with resins and applied in solution, emulsion, or hot.

It has been found that the lanolin not removed from the sheet in cleaning will generally be incorporated with most lacquer and japans, whereas a mineral oil slush is not picked up by the lacquer or japans so it will not adhere to the sheet.

Rubber, Rosin and Asphalt—These may be added to oil to obtain increased viscosity. However, the use of soaps, petrolatums, and wool grease generally gives so much better results that they are rarely employed as thickeners.

Used together in solvent solutions these agents are sometimes applied like paints and give a relatively nonsticky, tough film suitable for the protection of small machine parts to be stored in bins or under similar mild conditions. Washing with kerosene instantly removes the film when the part is to be used.

Greases—The addition of soda or lime soaps converts oils to greases. The resulting products are usually excellent for slushing purposes and can be turned out covering a wide range of characteristics. In color they resemble the base oil used and in consistency they may be had light enough for dipping, though in general the heavier grades, which must be applied by hand, are to be preferred.

Corrosion Inhibitors—Oil soluble chromates, particularly sodium dichromate, are sometimes added to slushes. They are claimed to be particularly effective in preventing "underfilm corrosion". Whether their use is beneficial or actually harmful has been a source of much controversy and it can only be pointed out here that some users of slushes find them satisfactory; whereas others manage nicely without them.

Such materials as red lead, blue lead, and zinc chromate, also occasionally find their way into slushing compositions. (See note A on next page.)

Typical Applications—The following examples may assist in visualizing the applicability of slushing compounds. In each case cited there may of course be alternative procedures which will give as good or better results.

Ball Bearings and Races—After careful cleaning to remove grinding compound, pack with an amber petrolatum and wrap in paper.

Small Auto Parts for Service Departments—Treat as above or coat with asphalt paint by dipping.

Razor Steel to Be Heat Treated—Dip in 50/50 mixture of 500 viscosity pale mineral oil and amber petrolatum.

Cold Rolled Auto Sheet—Same as above or coat with solution of lanolin.

Freshly Machined Car Wheel Journals, Roll Necks—Smear a handful of grease on machined surface before removing from lathe.

Exposed Gears and Similar Parts on Logging Machinery—Smear with heavy black grease which will also serve as lubricant.

Removal of Slushing Compounds—Frequently the part slushed will in subsequent service require lubrication. In this case a slushing agent should be chosen which itself either will prove a satisfactory lubricant or will not objectionably contaminate the lubricant to be used. Mineral oils and petrolatum mixtures are to be preferred since fatty oils and rosin often have a deleterious effect on lubricating oil. Greases may be used wherever grease lubrication would be permissible, otherwise they had better be avoided. When these precepts are followed no particular effort need be made to remove the slushing material.

Surfaces subsequently to be painted must be carefully cleaned since with most slushing agents any traces remaining prevent the proper adhesion and setting of the paint. This is even more true when lacquer is to be used. Washing with hot soap and water is perhaps the most effective for removing slushing agents. It must be followed by thorough rinsing, quick drying, and often buffing to remove any light rust formed during drying.

In some cases the agent can be burned off in a suitable oven and the metal then buffed. Frequently solvents are used to effect removal of the oil or slush but this procedure is always costly and often hazardous.

Slushing compounds employed for most other purposes are little affected by subsequent uses to which the article is to be put. They need merely be wiped from the surface with a rag or waste. Where a particularly heavy coating material has been used a kerosene soaked swab is more efficient.

Precautions—Where inflammable volatile solvents are employed they constitute not only a fire hazard but the vapors are themselves harmful when inhaled. The noninflammable chlorinated solvents are even more objectionable in this respect and should only be used where good ventilation is available.

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Note A—Recently a mixture of 10% aluminum stearate, 10-13% butanol, 5-6% triethanolamine, and the remainder lard oil has been recommended by the Ethyl Gasoline Corp. for the protection of the interior of airplane engine cylinders when the engine is to remain idle for some time, especially in tropical regions. The composition has the ability to neutralize residual corrosive materials as well as protect against the customary atmospheric corrosion. This and similar mixtures may well find use where related specialized corrosion problems are likely to arise as in the protection of rifles, artillery, etc., which after firing are difficult to free of residual corrosive materials.

Composite Steels

By T. S. Fitch*

Definition—"A Composite Steel shall consist of two or more components of which the smallest shall comprise at least 3% of the total mass."

Characteristics—The advantage of using a composite steel may be any one of, or a combination of, the following: (a) Hard working area with a tough backing. (b) Reduction of original cost where one of the components is expensive, and cost of production is not too great. (c) When the finished article must be hardened the backing may be drilled after hardening. Likewise, some straightening is possible after hardening if warpage has taken place. (d) Improved shock resistance. (e) Surface protection against corrosion and oxidation. (f) Inasmuch as each component has a period of vibration of its own, there is a dampening effect upon the vibration of the composite steel as a whole therefore lessening chattering. (g) Special physical properties as a result of combining dissimilar materials, such as thermostatic effect in lead-in wire for electric bulbs to match thermal expansion of glass.

The chief disadvantage of composite steels, both in production and fabrication, is warpage. This may be due to differing expansion characteristics or to an unbalanced arrangement of the components so that the stresses do not offset one another. In many instances the quality of the weld is extremely important, and not all of the methods which are to be described necessarily result in satisfactory welds; the application for which the composite material is to be used may determine the best method to utilize.

Fig. 1-6 indicate an average example of various types, and each sketch is accompanied by a list of typical applications.

Blacksmith or Forge Weld Method—The "blacksmith's weld" or "forge weld" is undoubtedly the oldest method for producing composite steels and it is also the simplest, but it is definitely limited to carbon steels or lightly alloyed steels. Any steel containing more than approximately 0.50% of tungsten, chromium, nickel or cobalt will yield uncertain results. Steels containing up to 1% of vanadium, manganese, silicon or molybdenum can be forge welded with a fair degree of success. The principle is the application of pressure to two or more pieces in contact at elevated temperatures (usually 2000°F. or higher). It is customary to employ borax or any other convenient flux, to absorb the iron oxide and thus leave relatively clean welding surfaces. The skill of the blacksmith is of considerable importance; if the pieces (particularly the steel) are left in the fire too long there is so much oxide formed that the borax will not absorb enough of it and a weak weld will result. Likewise, if insufficient borax is used too much oxide may remain.

The Casting Process—This is probably the oldest method which has been used for tonnage production. As its name implies, a composite ingot is produced by pouring one metal onto or about another. There are many variations in the technique so only the general methods will be mentioned:

(a) The earliest application was probably for the making of "soft center" plow shares. Molten high carbon steel is cast about a previously positioned iron insert so that the iron comprises about $\frac{1}{4}$ of the cross section and is located centrally. It is important that the insert be reasonably clean; it is usually pickled just prior to casting. It is also important that the insert be completely enveloped by the molten metal because it may be readily shown that no weld is actually produced in the ingot when one metal is cast around a relatively cold insert. If there is space for air to penetrate between the insert and the cast metal prior to further working an excessive amount of oxide forms on the surface of the insert and the cast metal. With carbon steels it is possible to produce a bond even if the insert is not entirely enveloped, but the weld will not be so good.

Casting mild steel around cold alloy inserts (particularly stainless steel) is being done commercially in this country. For a full description of the process see the article entitled "Stainless Clad Steels" on p. 1162. It is especially important that the inserts be completely enveloped by the cast steel and that special precaution be taken to ensure that the inserts shall be as clean as possible when the mild steel is cast.

(b) Various attempts have been made, with varying results, at casting metal

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onto or around an insert that has been heated previous to casting. When the inserts are heated in gas, coal or oil fired furnaces without some surface protection a poor weld results when alloy inserts are involved.

(c) In England, particularly, successful composite steels have been produced by casting one steel into a mold divided by a removable partition, then removing the partition and quickly casting the second steel into the mold. Since both metals are in the fluid or nearly-fluid condition good welds may be produced.

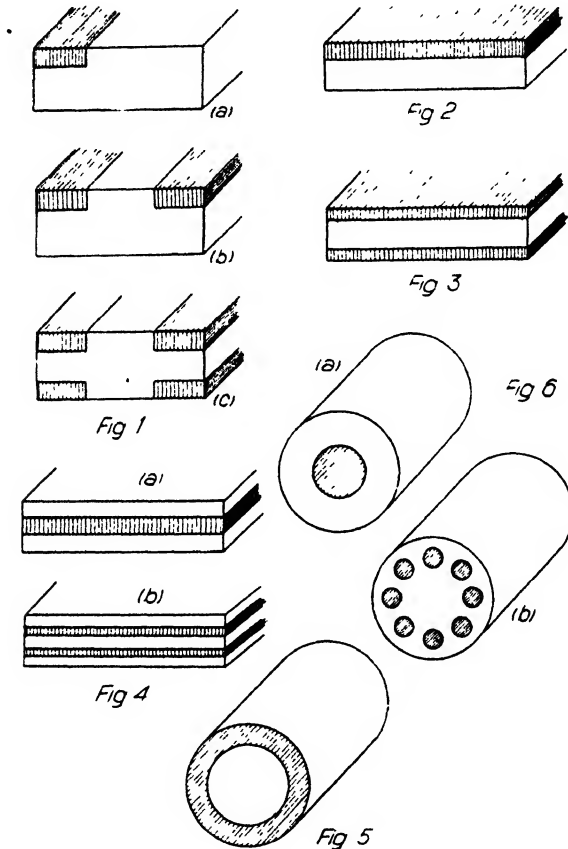


Fig. 1—Hacksaw blades; shear blades; knives of all types; and lathe tools.

Fig. 2—Blanking, piercing, drawing, forming and stamping dies. Single-bevel knives; circular knives and cutters; abrasion resistant parts; corrosion and heat resisting parts (see article on Stainless Clad Steels), and machine ways.

Fig. 3—Soft center plow shares with stainless steel cladding. Applications involving heat conductivity such as cooking utensils, vats, griddles, electric contacts.

Fig. 4—(a) Double bevel knives. (b) Vault steels.

Fig. 5—Reamers; drills; broaches; corrosion resistant parts; heat resistant parts; and decorative trim.

Fig. 6—Jailbar (b); stoker bars (a) or (b); special structurals (a) or (b); dies (a); punches (a); pivots (a).

(d) By increasing the surface of the insert it is possible to improve the bonded condition of a composite steel. To accomplish this increase in the surface area, serrations are cut in the insert as shown in Fig. 7.

(e) It is also possible to make a satisfactory composite casting where the strain on the weld is not great by "keying" the insert into the backing. Fig. 8 shows how an insert might be cut so that it would be mechanically held in the casting.

(f) One of the newest methods is to electropickle the insert to be absolutely certain of removing all oxide, then move it (wet) into a plating bath and deposit

thereon a protective coating. This coating is usually iron because it is easy to weld onto, produces no zone of weakness as would copper, and also because iron has a high melting point. The electroplated insert is then placed in a mold and the molten metal is cast thereabout as already described. Excellent welds are obtained by this method.

(g) In another method, a coating is placed on the side of the mold wall prior to casting, which coating is composed chiefly of ferroalloy of the desired parent

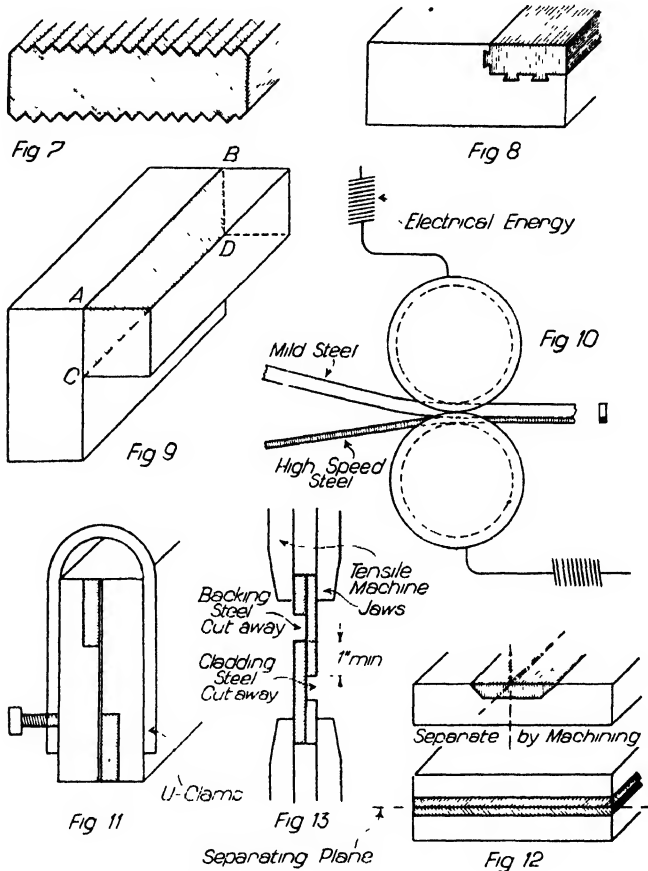


Fig. 7—Bond improved by cutting serrations in the insert.

Fig. 8—Method of keying insert into the backing material.

Fig. 9—Composite die section made by welding insert.

Fig. 10—Composite hacksaw strips made by electric resistance welding.

Fig. 11—Multiple heat treatment in clamps to offset stresses.

Fig. 12—Assembly or ingot made double the desired size so that stresses are partially offset.

Fig. 13—Tensile Test of the welded condition of composite steel.

metal plus certain chemicals so that controlled cladding ($\frac{1}{16}$ – $\frac{1}{2}$ in.) results when the molten metal is cast into the mold. This method can also be adapted so that cladding can be placed on previously cast or forged articles.

Generally speaking, it may be said that the casting method is convenient for tonnage work; it permits of producing sections which are irregular in themselves or in which the inserts are irregular; and it is generally the least costly.

The Cementation Process—This process utilizes cements which are in many cases complicated combinations in which the basic constituents are iron filings, silicomanganese, ferrosilicon, nickel and borax. Some of these cements are so

effective that it is merely necessary to squeeze the excess cement out and, after it has hardened, a good bond is evidenced. On large sections a heavy press is advisable, but on small tools (such as tool bits for lathes) the components may be squeezed and held until cold with a pair of tongs. The producers of these cements require that temperatures in the vicinity of 2300° be employed and they also recommend that the surfaces be machined prior to cementation.

One of the latest refinements of this general process has been applied to producing nonmetallic substances with metallic claddings; for example, wallboard with a thin cladding of stainless steel is made by putting a special cement on the non-metallic surface, placing the stainless sheet thereon, then putting them through rolls to bond the two components together.

Fusion Welding Processes—Many articles which come within the definition of composite steels, as it has been used throughout this discussion, are and can be produced by the fusion welding processes. For a discussion of Facing Surfacing, see page 1172.

(a) When the components are small enough in size the penetration of the welding heat may be sufficient to produce a strong joint between the components. For example, in the making of composite die sections it may be desirable to weld a piece of steel 1 x 1 in. onto a section of mild steel $1\frac{1}{2} \times 2\frac{1}{4}$ in. as indicated in Fig. 9. The welds are made along the lines A-B and C-D and, with proper control of the arc, good fusion may be effected to a depth of $\frac{1}{2}$ AC during each welding operation; thus the finished section will be completely fused throughout the entire weldable plane ABCD. When the strain on the joint is not to be excessive it may not be necessary that the entire plane be fused but this is a matter of trial and error.

(b) Electric resistance welding has been successfully adapted to the making of composite hack saw strips. Low voltage, high amperage current is conducted through rolls to the mild steel strip and the high speed steel strip, which are both held firmly together by the rolls as shown in Fig. 10. Likewise many other composite tools such as reamers, end mills and twist drills have been produced by resistance welding. Excellent welds may be effected in this manner but the method is generally confined to small sections—because of the abnormal cost on large sizes.

(c) For applications in which a cheap steel faced with a corrosion resisting, heat resisting or other expensive alloy surface is desired such composite steels are often produced by "spot welding" one to another. The result is a large number of welded spots surrounded by nonwelded areas so that such material is not as safely formed as a composite sheet or plate having a homogeneous welded condition. If the strain on the weld is not to be excessive composite plates thus produced will be satisfactory and the cost may be less.

The Assembly Process—This method involves the joining together of prefabricated bars or plates, then subsequently reworking the assembly to the desired finished form. For a complete description of this process see the article entitled "Stainless Clad Steels" on p. 1162. This method is advantageous in many cases because of its greater flexibility on small quantities as compared to any of the casting methods; also it is possible to control the relative proportions of the components more accurately. Generally speaking it is somewhat more costly than the casting process.

The article on "Stainless Clad Steels", as its title implies, deals only with the corrosion and heat resisting products but the methods described, particularly that method involving the electropickling and electroplating of a protective coating onto the insert or inserts, are equally adaptable to other steels.

Backings—Only recently has special consideration been given to the backing materials utilized in the production of composite steels. The problem is complicated by conflicting requirements, especially in cases where the insert is so placed that it tends to pull the bar out of shape. An important consideration is the desired physical characteristics of the backing material in the finished article; for example, a composite hacksaw steel should have as tough a backing component as possible without becoming too hard during the hardening of the blade; whereas, a composite stainless plate should usually have a soft back that may be readily formed. For any application involving heat treatment it would be ideal to have a backing with the same coefficient of expansion as the alloy in order to eliminate warpage. From the producer's point of view it would be ideal if the two metals had equal rates of elongation so that the composite product could be worked similarly to solid steels. Further, the value of the backing material must necessarily be considered,

because the additional cost of making composite steel has to be offset in some manner, else the selling price will be too high.

(a) The most often used backing analysis is S.A.E. 1020, which is relatively inexpensive, is easily obtained, is readily formed even after hardening, and is comparatively simple to weld. On the other hand, if the backing steel is preferred to be fairly tough then S.A.E. 1020 is not the best type; its coefficient of expansion differs appreciably from that of those alloys customarily used for inserts, which means difficulty in any heating or cooling operation; its rate of elongation is more rapid than the usual insert alloys; and it has a tendency toward enlarged grains when the composite product must be annealed after working. In spite of these drawbacks it has been and probably will continue to be the usual commercial backing for most applications.

(b) In cases where the comparative coefficients of expansion are most important a silicomolybdenum steel (carbon 0.10%, manganese 0.20%, silicon 1.50%, molybdenum 0.50%) has proven satisfactory. Also S.A.E. 2340 has given good results. These coefficients of expansion are more nearly equivalent to tool steels, particularly high speed steels, than any other relatively inexpensive steels so far tried.

(c) For applications such as chipper knives when the knife must have a good tough backing component to absorb severe shocks, the following analysis has proven excellent: C 0.28-0.34; Mn 0.45-0.65; Si 0.35-0.55; S and P 0.020 Max.; Cr 0.85-0.95; V 0.20-0.25.

(d) For applications such as hacksaw blades where it is desirable to produce some hardening effect in the backing steel the following analysis has proven satisfactory: C 0.42-0.50; Mn 0.50-0.65; Si 0.20-0.40; S and P 0.020 Max.; Ni 1.25-1.45; and Cr 0.50-0.65. This results, after proper hardening, in a backing that has springiness and superior abrasion resistance. It is somewhat harder to weld properly, but this can be circumvented by the proper choice and manipulation of method.

These analyses should not be considered as hard and fast rules because the carbon content is most important and alloys of various combinations may be added to vary the physical properties.

Heat Treatment—The difficulties in the proper heat treatment of composite steels are dependent on where the insert or inserts are located, relative proportion of insert or inserts to backing component, relative analyses, and suitability of equipment. Considerable experience is usually necessary before fully satisfactory results are obtained, but fortunately a composite steel can usually be straightened somewhat after hardening and tempering.

(a) *Design*—The significance of the location of the insert or inserts is only important when the coefficients of expansion differ. If the tool steel and backing steel had the same expansion rate the warpage would be no worse than on a solid piece of either steel. When the insert is symmetrically placed within the mass of the composite cross section, there is no abnormal warpage because the deformational stresses offset one another; for example, a composite bar having a high carbon, high chromium alloy steel center uniformly surrounded with S.A.E. 1020 will not pull out of shape during heat treatment. When the insert is along one edge or entirely covering one flat surface the composite steel tends to bow; when the insert is in one corner the bar tends to be pulled out of shape in two directions so that this form is the most difficult to heat treat.

(b) *Relative Proportions*—The smaller the amount of tool steel as compared to the amount of backing the less the tendency will be toward warpage, which is obvious because the net deformational strength is directly proportional to the relative masses.

(c) *Relative Analyses*—The greater difference in the thermal properties of the component metals the greater will be the warpage effect in heat treatment. Inasmuch as the thermal properties are primarily determined by the analyses (also somewhat dependent on grain size) it is obvious the relative analyses are important.

(d) *Air Cooled*—Any composite steel composed of materials that can be cooled in air may be held straight in a press after it is removed from the furnace. In some cases, particularly where the insert is in one corner, a special die is made up for the press with a groove cut in the die so that the bar is sure to be straight lengthwise as well as on the flat.

Multiple Heat Treatment—Small composite sections may best be heat treated in pairs. About the maximum convenient size is $\frac{1}{2}$ x 6 in.; bars larger than this have too much distortion strength. The clamps would have to be so big to hold

them that handling would be inconvenient, and unless the clamps were carefully designed nonuniform heating might result. The intention of this multiple heat treating method is to so arrange the bars within the group that the stresses will offset one another. A typical example is shown in Fig. 11.

Presetting Method—This method requires considerable experience to learn just how much and in what direction to deform the bar prior to heat treatment so that the stresses during treatment will cause it to return to reasonable straightness. This method is not recommended when the insert comprises 40-60% of the total mass; for reasons sometimes seemingly unexplainable, one bar may distort one way and the next may distort the opposite; however, the distortion is usually not so great in these cases that the bar cannot be straightened after hardening and tempering.

The section should be so treated that, after tempering, the insert is convex. There need be no fear of straightening when the tool steel is under compression as the backing steel will elongate readily.

Annealing and Normalizing—The annealing or normalizing of composite steels should be considered from the producer's as well as the user's viewpoint. The simplest method of producing composite steels in which the insert mass is unsymmetrically arranged in the backing is to make the assembly or ingot double the finish form so that the stresses will at least partially offset one another; in this way they will have less trouble in the rolling and also less trouble in the annealing. Two typical forms are shown in Fig. 12. In annealing composite steels it is advisable to use the lowest temperature possible to avoid abnormal grain growth in the backing steel.

Testing—Composite steels, because of the presence of materials with dissimilar characteristics, present a peculiar and often difficult testing problem. Because of the numerous modifications in composite steels it is not practical to prescribe testing methods which will apply in all cases. The following comments are intended to be helpful in establishing and interpreting tests.

The simplest method for testing the welded condition is the bend test. For material clad on one side, it is recommended that one piece be bent with the cladding on the outside and a second piece with the cladding on the inside of the bend. In all cases it is wise to bend the piece back again because an improperly welded composite steel may bend one way without showing a fracture at the weld.

A more severe and reliable test of the welded condition may be made by pulling in a tensile testing machine a sample which has been prepared as shown in Fig. 13.

Welded flat tensile test specimens may be pulled satisfactorily and the results will usually be found reasonably accurate. In the case of round specimens which are machined from bar stock, the proportion of inserted material to backing material may be changed by the machining. Allowance should be made for this in evaluating the results.

The reliability of the various hardness testing methods depends chiefly upon the thickness of the piece to be tested. Samples $\frac{1}{8}$ in. thick or greater may be safely tested by Rockwell hardness testing devices or by any of the testing machines involving the drop and rebound principle such as the scleroscope. Samples lighter than 0.0625 in. are best tested on the drop and rebound principle machines. Actually the surest means is to grind or otherwise remove all the steel except that on which the hardness is wanted, then test the remainder.

In making cup tests on clad sheet and strip samples there will be some variation depending on the direction in which the cup is drawn; if the insert material is on the inside of the cup the draw tends to be better. The reason for this is that the soft backing material supports the harder insert material during the draw. Users who desire to determine the drawing properties should draw the material so that the stainless is on the same side as it will be in the finished product. Producers should indicate whether the cladding was on the inside or outside when reporting cup tests.

General—There are two methods in common use for indicating the location and extent of the insert in a composite steel: Acid etching and heat coloring. A warm 50% nitric acid solution will bring out the insert in approximately 30 sec.; the acid may be washed off with warm water; and lacquer, oil, or vaseline may then be put on the etched plane to protect it from subsequent corrosion. Heat coloring is often used when the insert is a tool steel or S.A.E. grade which can be turned straw or light blue by exposing the end to a temperature which does not adversely affect the structure of any of the components; it is also well in this case to protect

the colored plane with lacquer, oil, or vaseline. This latter method renders the insert more readily visible but is not so fast as the acid etch method.

When any machine work is done on a composite tool steel prior to heat treatment there is some hardening effect and thus a strain is set up. This strain is preferably relieved by normalizing before proceeding with the hardening. The warpage in the hardening and tempering may thus be reduced. This machine strain is not a serious factor on short sections (18 in. or less).

It is in the fabrication of composite steels that much of the advantage of these materials is found. For example, a tool steel composite bar may be 25% tool steel, and the balance soft steel which can be machined more quickly. Clad plates may be bent or formed more readily than solid material of the same analysis. Composite steels in which the inserted material is symmetrically arranged may be cold drawn faster.

The fusion welding of composite steels (this does not refer to the production of the composite steel itself) requires some special precautions: (a) Due to the tendency of the alloys in the insert to migrate into the unalloyed steel it is well to utilize welding rod having higher alloy contents than the insert steel; this tends to replenish any loss due to migration. (b) In electric arc welding the amperage should be maintained as low as efficient because excessive heat tends to admix the backing and insert steels. In the case of high alloy composite steels the carbon in the tool steel might be so reduced as to impair its desirable properties; also the backing steel might be embrittled at that point by carbon enrichment. (c) Thick composite plates ($\frac{1}{2}$ in. or more) should be bevelled away from the insert, then lay a small bead down along the abutting insert edges, turn the two over and fill in the back with whatever rod suits the conditions. (d) In the stainless clad steels it is well to add a stabilizing material such as titanium or columbium to the stainless analysis to avoid intergranular corrosion in subsequent welding; thus annealing can be eliminated after welding. (e) High grade shielded arc type electrodes or gas filler rods are recommended.

A skilled operator with suitable equipment can soon learn to weld composite steels in a wholly satisfactory manner.

For complete recommendations on sizes of rods, current intensities, and manipulation see page 220 on welding as well as other handbooks on fusion welding.

Stainless Clad Steels

(Sheets and Plates)

By L. C. Grimshaw*

Plates and sheets of mild steel faced with stainless steel have been produced commercially only within the last few years. The stainless steel layer usually constitutes 10-20% of the thickness of the plate or sheet, and either one or both sides may be coated. Such clad steels have been developed largely to reduce the cost of stainless plates, particularly for the many applications where only one side of the plate needs to be stainless.

Strength of Bond—The bond between the mild steel and its stainless "cladding" must be strong enough to withstand stresses incident to fabrication into the finished product. Stainless clad steels are produced that can be bent, spun into deep heads, and deep drawn without damage. Often the bond must be strong enough to withstand great stresses due to a difference of expansion between the stainless facing and the backing when heated and cooled repeatedly.

Methods of Bonding—Two clean pieces of mild steel will readily weld together if hammered while heated. With less facility, and usually with the aid of a flux, high carbon steel and mild steel can be similarly welded. Indeed, the first commercial use of laminated steel was probably such a combination used for turning plows, manufactured by John Lane in 1868.

Nickel and mild steel, and copper and mild steel, can be welded together by heat and pressure alone. High alloy steels cannot be successfully welded to mild steel by this method without considerable modification. They were first successfully welded by the method of "casting on," a method relatively old, and often referred to in technical publications at the turn of the century.

Stainless clad sheets and plates are successfully produced by the casting method. In one casting method, two cleaned stainless steel sheets are placed face to face with a separating material between them, and fusion welded together around their edges. These two sheets are then set upright in a mold, and mild steel is poured all around them. The composite ingot is hot rolled until it has received the desired amount of reduction, the edges of the rolled composite plate are trimmed off and it separates into two sheets, each clad on one face with stainless steel.

Temperature control during casting is important. Since there is oxide on the surface of the stainless steel insert in the ingot, no true weld can be made until this oxide has been broken up by elongation into small islands.

On account of the fusion weld required in their fabrication, it is important from an economic standpoint that the clad plates be made large in size. There is a limit to the amount of reduction that can be given by hot rolling before the separating material between the two stainless sheets fails to do its duty because of thinning out. The above method has been used to produce plates up to 1½ in. thick, but only of small size (1,500-2,000 lb.), and not thinner than 18 gage.

A different method for producing stainless clad plates by casting is said to be in successful use in England. Grooves are cut in opposite sides of a mold, in a position such that a spacer plate slid down in these grooves divides the mold in a ratio of about 3:1. Mild steel is cast into the larger space. After a short time the spacer plate is withdrawn, and stainless steel is cast into the remaining space. After cooling, two such ingots are surface ground, and their stainless faces placed face to face with separating material between them. "Straps" of mild steel are then fusion welded all around the sides to hold the two-high assembly together. The assembly is then heated and rolled, and separated into two clad plates by shearing off the edges.

It is not known to the writer how economical the above method is, but it would appear subject to all the limitations of the first casting method described.

A method, now in the early stages of development, appears to be especially suitable for the production of thick plates, in which the stainless steel may well be much less than 10% of the plate thickness. The stainless steel (usually 18-8) is deposited from electrodes onto the mild steel slab. This forms a good weld, and only enough hot rolling need be given to the slab to eliminate the cast structure of the stainless steel, to facilitate discovery and elimination of pin holes in the deposit, and to smooth the surface.

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Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

In another method of bonding a thin sheet of iron is placed between the stainless and the mild steel, fusion welded around the edges to prevent scaling, heated and hot rolled. The thin sheet of iron is said to have a beneficial cushioning effect, and after a great deal of elongation by rolling a satisfactory weld can be made. Oxides are troublesome, and the results too uncertain for this method to be commercial. No matter how carefully stainless steel is cleaned, it becomes covered with an invisible oxide film as soon as it is exposed to air, and the oxide thus formed must be broken up by elongation during rolling into small islands before a weld can be made. It is undoubtedly easier to weld stainless steel to iron as the carbon content of the iron becomes lower. A variation of the above method would be to decarburize the surface of the mild steel before attempting to make the weld, and leave out the thin piece of sheet iron. A zone of pure iron in the weld is a zone of weakness, and should be reduced as much as possible.

A commercial method in growing use produces a good weld by removing the invisible oxide film on the stainless steel by anodic pickling in hydrochloric acid, and electrolytic iron is deposited upon a chemically clean surface. Iron plating is commenced while the stainless sheet is still wet with acid and free from oxide film. The iron plating is usually about 0.012 in. thick. Any kind of steel, so plated with electrolytic iron, will weld to mild steel if heated and rolled. Commercial production of stainless clad plates by this method is as follows: "Separating material" is placed between the juxtaposed faces of two sheets of stainless steel, and a watertight fusion weld made around the edges of the sheets. They are then pickled, the unit is iron plated, and placed between two thick plates of mild steel. This assembly is fusion welded together around the edges, both so as to hold it together as a unit during hot rolling and to exclude air that would scale the surfaces to be welded. It is heated and hot rolled. During the first pass a weld is made, and rolling is continued to produce plates of the desired size. The composite assembly behaves like mild steel, and may be cross rolled if necessary to increase the width. When the edges are trimmed off, the composite plate separates into two plates, each clad on one face with stainless steel.

If the stainless steel is an austenitic one (the 18-8 variety) it will expand a great deal more than the mild steel when it is heated for rolling, and so must be left free to expand laterally between the mild steel plates. Such an assembly ready for heating, rolling, and welding, is shown in Fig. 1. The expansion space is not necessary for martensitic or ferritic stainless irons.

During hot rolling, even with little reduction, an excellent, oxide free weld is made by this method. Diffusion soon eliminates the zone of electrolytic iron in the welded plate, this being less than 0.002 in. after 12:1 reduction of the two-high assembly. Diffusion is rapid while the plate is hot. Such plates may readily be spun into deep heads, or drawn.

Stainless clad plates are also successfully produced by iron plating stainless steel in the above manner, and casting mild steel around it. The surface of the stainless steel is as free from oxide as in the assembly method, and it is more satisfactory to cast mild steel against the iron plating than against the stainless steel itself.

In most of the above methods, whether by casting or assembling, it is common practice to prepare a "sandwich" with mild steel outside, stainless sheets inside, and separating material in the center, the "sandwich" being held together as a unit either by an excess of cast metal or by fusion welding the edges. The difference in the hot working properties and in expansion of the stainless and mild steel tends to produce curled plates. By rolling as a "sandwich," curling is prevented. Hot rolling of single clad sheets is not done unless the finished sheet can be straightened cold. Hot straightening is impracticable, as the straightened sheet again curls when cooling, particularly if clad with 18-8 stainless steel.

The separating material used in two-high assemblies is commonly a mixture of aluminum oxide and lacquer, applied like paint, so as to spread thinly and evenly over the steel surface. The lacquer dries in a short time, leaving the fine oxide powder adhering to the steel. Any inert oxide can be used, but silicate of soda should not be substituted for lacquer unless all moisture is driven off at a high heat prior to assembling for rolling.

Another commercial method of making stainless clad plates is to bond a stainless sheet to a mild steel plate by a special method of resistance welding. The electric current passes, not through the thickness of the mild steel plate, but from one spot on the stainless sheet through the surface of the mild steel to another spot on the stainless sheet only a short distance away. This method bonds by means of

a great number of resistance welds, placed closely together all over the sheet. Such a sheet is never rolled except in forming rolls. The bond, though discontinuous, is strong enough to withstand the stresses incident to fabricating into spun heads and heat treatment. By this method composite plates of any convenient size are provided, and thick plates are covered with a stainless steel protecting sheet of far less than 10% of the plate thickness. By this method many large tanks, cracking vessels, and chemical towers have been made.

Applications of Stainless Clad Steels—Stainless clad steel may be useful either because of lowered cost, improvement of physical properties, or both. Lowered cost appears obvious, but is difficult to attain. The stainless sheets used for cladding must have at least one perfect surface, and be flat. The mild steel plates must be flat if the assembly method is used.

The fusion welding of an assembly is expensive, and stainless rod must be used for weld A (Fig. 1). If the casting method is used, there is a waste by trimming.

Since clad plates are rolled in pairs one clad plate is always left over when only a single clad plate is desired.

However, many clad sheets are used because of the physical properties obtained. If the weld is a good one, cooking vessels such as are used in the varnish, canning, and soap industries are best made out of stainless clad steels. The inside of such vessels is required to be stainless, but a solid stainless steel vessel is subject to hot spots and low heat conductivity. The clad vessel combines the stainless surface with the excellent heat conductivity of mild steel.

It is often desired to use the 12 or 28% chromium ferritic stainless irons, but they are difficult to fusion weld. Ferritic stainless iron used as cladding on ductile mild steel solves these problems, and such clad steels are finding increasing uses.

Austenitic steels, such as 18-8, have a coefficient of expansion greater than that of mild steel, so for stainless clad plates used at elevated temperatures the bond must be good. The high quality of many commercial bonds is proved by the wide use of such material at elevated temperatures. If the fabrication of the vessel requires fusion welding, and intergranular corrosion is feared, an 18-8 that contains a stabilizing element is advisable, because a stabilizing heat treatment at 2000°F. is undesirable when applied to the mild steel backing, and would also probably warp the vessel.

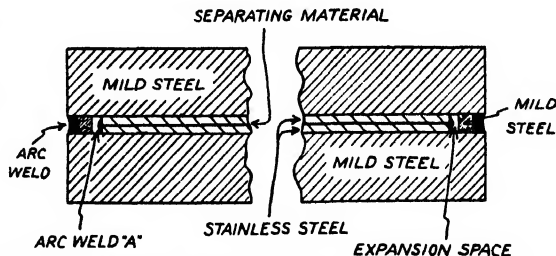


Fig. 1—Assembly ready for heating, rolling, and welding.

Nickel and Nickel Alloy Clad Steel

By W. G. Theisinger* and F. P. Huston**

Nickel clad steels are composite materials made up of an open hearth steel base and a layer of pure nickel or an alloy of nickel-chromium bonded to it on one or both surfaces.

The composite plate is formed by pressure welding the clad material to the steel slab in a rolling mill at a temperature of about 2200°F. Thorough cleaning and protection of the bonding surfaces during heating insures an intimate bond between the cladding and the base plate. A reduction ratio ranging from 8:1-16:1 is generally used. A solid solution of nickel and iron is formed at the junction plane of the two metals.

The ratio of the cladding material to the base plate is usually expressed as a percentage of the total thickness of the composite plate. For example, a ½ in. plate clad 10% one side only, consists of about 0.45 in. of steel and about 0.05 in. of pure nickel and a ½ in. plate, with 20% cladding, consists of about 0.10 in. of pure nickel and 0.40 in. of steel. The same order of thicknesses of cladding are produced for plates clad both sides. It is the usual practice when cladding both sides to use an equal thickness of either nickel or the nickel-chromium alloy, although different thicknesses may be applied. Plates clad one side with nickel and one side the nickel alloy may be obtained for special purposes. Nickel clad steels are regularly supplied with standard claddings of 5, 10, 15 and 20% with flange quality steel of 55,000 psi., minimum tensile strength, as the standard basis metal.

The clad surface possesses the same chemical and physical properties as would a solid, hot rolled nickel plate. It is bonded uniformly to the steel and does not separate from it as a result of changes in temperature, pressure (vacuum), or deformation in forming. Nickel clad steel is suitable for any conditions for which pure nickel is suitable. The clad plate is produced in sizes and gages generally comparable to plates obtainable in carbon steel.

Properties of Pure Nickel for Cladding—The modulus of elasticity of commercially pure nickel is 29,000,000-30,000,000, which is essentially the same as for steel, and its hot working range is likewise similar to that of steel. Its coefficient of expansion is close to that of steel, and for all practical purposes they may be considered identical. The melting point of nickel is 1455°C. ± 1 and that of steel which varies somewhat with the composition is somewhat below the melting point of pure iron, 1535°C. ± 3 .

The fact that the modulus of elasticity of nickel is the same as that of steel is of importance in a composite material such as nickel clad steel plate and insures an equal distribution of stress across the section of the plate with no sudden change at the interface between nickel and steel.

Properties of Nickel Clad Steel—Results obtained on an 8 in. tensile test specimen of ½ in. thick nickel clad steel with 10% cladding are as follows:

	Tensile Strength, psi.	Yield Point, psi.	Elong., % in. 8 in.	Reduction Area, %
Clad	60,600	40,400	30.0	57.2
Plate	60,800	40,200	30.5	59.0

To determine the value of bond between the nickel and steel, a clad surface was placed at right angles with the striking face and with one blow of a power hammer a 1 in. cube, with one face clad 20%, was flattened cold to ¾ in. thickness without rupturing the bond. To test the strength of the bond under sudden changes of temperature, a 10% clad plate (18 x 9 x ½ in.) with stiffeners welded to the steel side was heated to 900°F. and quenched in water at room temperature. No separation of the nickel layer occurred after quenching 30 times.

Utilization of Nickel-Clad Steel—Cold bending, flanging, forming, beveling, and the like, can be readily carried out on nickel clad steel. Generally, and especially when shearing and punching the nickel side should be up so as to prevent damaging the surface and to throw the burr on the steel side.

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Prepared for the Subcommittee on Metallic Coatings, H. S. Rawdon, General Chairman.

Annealing—Annealed plate is required for severe cold working operations, such as in pressing heads and die work. To anneal, heat the plate to 1650-1750°F., hold at temperature from 1-3 min., and allow the plate to cool in the air.

A fuel of low sulphur content (not over 0.5%) should be used to prevent embrittlement of the nickel layer. A covering of lime on the nickel surface is helpful.

Heating—When heating nickel clad steel, either for annealing or for hot working, the plate is charged into the furnace which is at temperature. The atmosphere should be reducing and the flame should not strike the surface.

Hot Working—The hot working of nickel clad steel entails no unusual difficulties if the proper conditions for heating are maintained. No change need be made from usual steel practice as to temperatures, amount of work done on each heat, or the general methods used in performing the work.

Joining—Joining nickel clad steel plates and heads to form pressure vessels and tanks may be done by gas or electric welding, or riveting and caulk welding. With all methods, the nickel surface should be made continuous by welding all junctions in the nickel side of the joint with nickel filler metal. In general, the corrosion resistance of such welds is not inferior to that of the nickel surface.

Metallic arc welding is the method generally used. The plates are beveled as shown in Fig. 1, and the vessel is assembled by "tacking" on the steel side. The weld on the steel side is then made with a covered steel electrode, no change from standard practice for welding plain steel is required. A narrow groove on the nickel side is then chipped to a depth at which the chip no longer shows parting. The width and depth of the groove vary with the thickness of the cladding layer but should be kept to a minimum. The width is usually $\frac{1}{4}$ in. and should never exceed $\frac{3}{8}$ in., even in 1 in. plate. The welding on the nickel side is done with coated nickel electrodes. If two beads are required the slag should be completely removed from the surface of the first bead before the second is deposited. Butt welding is most commonly used but the lap, and the butt-and-strap joint are used also.

Carbon arc welding, on account of the slow speed possible, is only occasionally used for welding nickel clad steel but yields strong, dense welds of high ductility. Acetylene welding gives satisfactory joints in nickel clad steel and no change from regular procedure is needed in welding the steel side. However, in welding the nickel side it is important to maintain a slightly reducing flame. The intense flame that yields entirely satisfactory welds in steel gives brittle and spongy welds in nickel. Bare nickel, gas welding wire is used, without flux.

Nickel clad steel may be welded in all positions such as are encountered in erection work by any of the methods mentioned. In vertical welding it is advisable that the weld be started at the bottom and worked toward the top, rather than in the reverse direction.

Welds in nickel clad plate meet the requirements of the A.S.M.E. Boiler Code. Samples of plates welded as described above were stress relieved at 1150-1200°F. and gave the following results:

Tensile Tests of Welds

	Tensile Strength, psi.	Yield Point, psi.	Elong., % in 2 in.
Full section	65,300	40,700	25.0
Reduced section	59,800	40,300	22.2

Bend Tests

	Elong., % in 1 in.
Steel weld, outside surface.....	31.0
Nickel weld, outside surface....	37.0

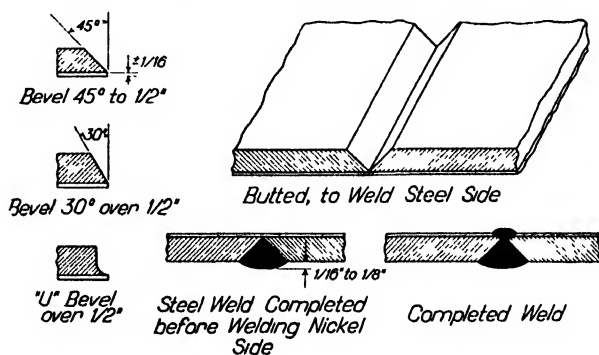


Fig. 1—Beveled butt joints

Design—A continuous nickel surface should be maintained in the fabrication of pressure vessels and other equipment. Jackets are welded or riveted to clad vessels and any type of bottom outlet, either in solid nickel or nickel clad steel, may be attached. Forged, tapped welding flanges in solid nickel are used. Practically any formed shape obtainable in steel is obtainable also in the nickel clad material. The material responds readily to hot spinning, hot and cold pressing, and hand shaping in the production of various shapes.

Nickel-Chromium Clad Steel—This alloy contains 78-80% nickel, 12-14% chromium, and 6-8% iron, combines a high degree of resistance to corrosion with high strength and good working properties.

The manufacture of this nickel-chromium clad steel is similar to that of nickel clad steel. It can be fabricated with the same facility and the welding procedure is similar. In the welding of the clad surface of the plate, a covered electrode containing 80% nickel and 20% chromium is used. This insures deposited metal of approximately the same composition and corrosion resistance as the cladding.

Lead Coatings

By J. L. Bray*

Lead, and lead-rich alloys, as protective coatings on steel possess the advantage of being (1) malleable, (2) resistant to corrosion by most acid fumes, (3) low priced, (4) readily available; but also the disadvantages of being (1) difficult to apply, (2) not resistant to abrasion, (3) subject to the formation of pin holes and (4) cathodic to iron. The difficulty of coating iron and steel with lead results from the fact that the two metals are immiscible. The success of any lead coating process must depend upon either (1) mechanical adhesion of the coating to the base or (2) chemical adhesion through the medium of some other element such as tin, mercury, antimony or zinc.

Low Alloy Coatings—The application of coatings of the lead alloys of very low alloy content usually consists in coating the pickled or cleaned surface with another metal or an easily reduced salt followed by immersion in molten lead or by the addition of a small amount of a suitable metal to the molten lead, which metal will promote adherence to the steel base on immersion in the molten lead bath.

Lohman¹ devised a process for applying a coating of lead to steel involving cleaning in sulphuric acid followed by dipping in a bath composed of HCl, HgCl₂ and NH₄Cl. After drying, the piece was dipped in molten lead at a temperature of 950°F. Although coatings of superior merit could be produced, the process was not commercially successful on account of the serious hazards resulting from the use of mercury. Another experimental process,⁴ involving the use of antimony as a binding agent, consisted essentially in (a) immersion of the cleaned piece in a solution of SbCl₃ until the surface turned black, (b) washing, (c) treatment with ZnCl₂, (d) immersion in molten lead and (e) cooling in oil. A process somewhat similar, employing phosphorus in the form of tin phosphide as a binding agent, has been commercialized to a considerable extent. In a recently announced process by Garbutt and Butterfield,¹⁰ the article after cleaning with caustic and acid, is passed through an aqueous solution of ZnCl₂, then through a molten flux of NH₄F and glycerol and into the molten lead bath. It has not been commercialized as yet in this country.

Recently a process has been patented that involves the use of zinc as the bonding agent. The raw material is sheet steel or wire bearing a tight (thin) coating of zinc applied by hot dipping. After cleaning with a molten flux (NH₄Cl and ZnCl₂), the material is passed through a bath of molten lead-zinc alloy (645°F.), the zinc content of which must be kept at approximately 0.5% (the eutectic point). According to the most recent investigation,¹¹ zinc dissolves in lead in the solid state to the extent of 0.10% and the eutectic contains 0.5% zinc. In this eutectic, and in any slight excess of zinc (above 0.5%) in the lead, the zinc crystallizes in a needlelike form. The real binding agent of a lead-over-zinc coating is believed to be these needles of zinc which can attach themselves to the lead by solid solution of zinc in lead and to the sheet which has been previously coated with zinc.

High Alloy Coatings—The most familiar application of lead as a coating material for steel is terne plate (meaning "dull" as distinguished from a "bright tin" coating). The process of manufacture is similar to that employed for tin plate, so for a more detailed discussion of terne plate, see the article on tinning of steel, page 1106.

Pure Lead Coatings—No completely successful method of coating steel with pure lead by dipping has been developed. Lead clad articles with pure lead as the protective layer find many uses where apparatus for handling or storing corrosive liquids is concerned. They are usually made by flowing lead on a clean steel surface; by burning on a coating, which thus forms a continuous envelope over the entire surface; or by rolling on a layer of lead under considerable pressure. The surfaces are usually prepared by sand blasting. The bond is often a mechanical one.

Pure lead can also be deposited by electrolysis and this is the most satisfactory method for obtaining thin coatings. For certain small, irregularly shaped or special articles, lead plating is an important process. The lead thus deposited is very pure and has the superior corrosion resistance of a pure metal. Lead can be deposited from a variety of solutions, but the only ones which have found commercial application are the fluosilicate, fluoborate and perchlorate solutions. Electrolysis must

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be carried out at fairly low current densities (5-20 amperes per sq. ft.) and much heavier coatings must be applied than is necessary in nickel, zinc and copper plating for the lead thus laid down is prone to "pinhole." When heavy coatings of pure lead are required it is usually better and cheaper to cast these from pure lead than attempt to put them on electrolytically.

Developments in coating steel with lead by the metal spraying process have been encouraging, lead being one of the metals which are easily applied by this method. See the article on sprayed metal coatings, page 1115.

Copper Sheets—While copper, if properly cleaned, can be coated with pure lead, an alloy containing a little tin is usually employed since the bond is better and the surface freer from pin holes. Such lead coated sheet copper shows a marked resistance to corrosion and is used as a roofing material and for other building material.

Utility of Lead Coatings—Lead in contact with iron and wet with an electrolyte functions as a cathode. Hence, a lead coating cannot protect iron electrolytically as zinc can. The value of lead coatings results from the high resistance of metallic lead against most acids. All lead coatings are porous. However, these can be more or less completely sealed up in the case of sheet by slight rolling of the sheet after the coating has been applied. The results of weathering tests of long duration (10 years) by the A.S.T.M. have strikingly demonstrated the relative merits of lead coatings in atmospheres of different characteristics. Lead coatings can be used to best advantage in an industrial atmosphere where the air is polluted with sulphurous gases. Perforations (pores) in the coating are soon sealed by the products of corrosion after which the corrosion is exceedingly slight. Companion specimens, however, in rural or marine atmospheres (A.S.T.M.) have immediately developed severe pin hole corrosion. Under conditions of high humidity, some blistering (separation of the two layers) has been observed.

A thin coating of lead assists in drawing and stamping operations on sheet steel by its lubricating action. It is for this reason that terne plate is so widely used in the fabrication of containers. The drawing of metals into tube, rod and wire form can be greatly expedited by using a thin surface layer of lead as in the drawing of some of the high alloy steels.

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Copper Covered Steel Wire¹

By L. C. Whitney*

In many cases today, the engineering requirements on a material used demand a combination of properties that is not found in any single common metal or alloy. To develop these, composite materials are sometimes produced from metals whose combined characteristics meet the specifications. Copper covered steel wire, which is essentially a copper wire with a steel core, is an example of this. The copper exterior provides high electrical conductivity and good corrosion resistance, while the steel core allows the development of tensile strengths considerably above those attainable in hard drawn copper and bronze wires.

To produce this material, a round steel billet with properly prepared surfaces is preheated in a mold and molten copper is poured around it. After solidification, the composite billet is hot rolled to a rod. The composite rods are then heat treated or annealed and drawn into wire of the desired size.

The casting of molten copper around a heated steel billet with properly prepared surfaces produces a weld between the two metals. This weld withstands subsequent heatings, hot rolling, and cold drawing and the finished wire may be bent, twisted, or deformed without causing a separation of the two metals.

This composite wire is produced commercially in two grades which are based on the electrical conductivity of the material. They are the 30% and 40% grades, a designation which indicates the electrical conductivity as compared with that of a solid copper wire of the same cross sectional area. The electrical resistance measurements on each coil are maintained to the following limits:

Rated Conductivity	Max. Average Resistance for Entire Coil, Ohms per cir. mil-foot at 68°F.	Max. Resistance for Any Part of Coil, Ohms per cir. mil-foot at 68°F.
	35.26 26.45	39 18 28.59
30%		
40%		

In addition to the two conductivity grades, there are two grades based on the tensile strength of the wire. These are designated as "high strength" and "extra high strength" grades. Detailed information on the properties of individual wire sizes is given in Table I.

Table I
Properties of Copper Covered Steel Wire

Dia., In.	Breaking Load, Lb.			Weight ^a		Resistance, Ohms Per 1000 Ft. at 68°F		Cross Section	
				Lb. Per 1000 Ft.	Lb. Per Mile	40% Cond.	30% Cond.	Cir. Mils	Sq. In.
	High Strength 40% Cond.	30% Cond.	Extra High Strength 30% Cond.						
.4600	13,300	14,960	....	587.2	3,100	.1250	.1666	211.600	.1662
.4096	10,540	11,860	....	465.7	2,459	.1576	.2101	167.800	.1318
.3648	8,361	9,407	....	369.3	1,950	.1988	.2650	133.100	.1045
.3249	6,797	7,791	....	292.9	1,546	.2506	.3341	105.500	.08289
.2893	5,916	6,705	....	232.2	1,226	.3160	.4213	83.690	.06573
.2576	5,056	5,682	6,412	184.2	972.5	.3985	.5313	66.370	.05213
.2294	4,258	4,754	5,519	146.1	771.2	.5025	.6699	52.630	.04134
.2043	3,541	3,934	4,672	115.8	611.6	.6337	.8447	41.740	.03278
.1819	2,938	3,250	3,913	91.86	485.0	.7990	1.065	33.100	.02600
.1620	2,433	2,680	3,247	72.85	384.6	1.008	1.343	26.250	.02062
.1443	2,011	2,207	2,681	57.77	305.0	1.270	1.694	20.820	.01635
.1285	1,660	1,815	2,204	45.81	241.9	1.602	2.136	16.510	.01297
.1144	1,368	1,491	....	36.33	191.8	2.020	2.693	13.090	.01028
.1019	1,130	1,231	....	28.81	152.1	2.547	3.396	10.380	.008155
.09074	896.3	....	....	22.85	120.6	3.212	....	8.234	.006467
.08081	710.8	....	....	18.12	95.68	4.051	....	6.530	.005129

*There is a slight difference between the weights of 30% and 40% conductivity wire. These figures represent the average for both materials.

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¹Copper covered steel wire is sold under the trade name Copperweld.

To insure a uniform coating of copper of the desired thickness on the wire, all coils are tested with a magnetic testing device which measures accurately the copper thickness at any given point. By means of such equipment, it is possible to guarantee a minimum copper thickness at any point around the circumference of the wire of 10% of the wire radius on the 30% grade and 12.5% on the 40% grade.

Physical and electrical constants and specifications on copper covered wire are as follows:

Average weight of wire—8.15 g. per cu. cm. at 68°F. (equivalent values are 3.533 lb. per inch-foot and 0.002775 lb. per cir. mil-1000 ft.).

Coefficient of linear expansion—.0000072°F.

Temperature coefficient of electrical resistance for wire—.0021 per °F.

Modulus of elasticity—24,000,000.

Facing or Surfacing by Welding*

Facing or surfacing is a process of welding onto wearing parts (either old or new) a facing, edge, or point of a hard metal that is resistant to abrasion. Hard facing is a surfacing operation that has proved to be an easy and economical means of keeping equipment in good operating condition, without losing time for repair or replacement of worn parts. There are also soft surfacing operations, such as for example, applying bronze bearing metal.

Hard Facing—Hard facing was originally applied only on metal working dies, oil well drilling tools, and certain types of excavating equipment, but other applications were soon found in almost every field, so hard facing is now an important factor in the welding industry.

The major cost reducing features of hard facing may briefly be summed up as follows: 1. Longer life of equipment; 2. Fewer replacements with resultant savings in labor charges and lost production time; 3. Utilization of cheaper base metal for wearing parts; 4. Salvaging or reclaiming of worn parts; 5. Savings in power consumption; and 6. General increase in operating efficiency.

No single grade of hard facing material is satisfactory and most economical for all applications. For the requirements of hardness, toughness, shock resistance, corrosion resistance, and other qualities, various hard facing alloys of widely different compositions have been developed. These may be divided broadly into five groups.

Group 1—Alloy steels consisting of an iron base with less than 20% of alloying constituents are included in this group. Alloying constituents consist mainly of chromium, tungsten, manganese, silicon and carbon. These alloys are relatively low in cost and while not as hard as higher priced hard facing metals, they possess greater toughness and shock resistance. However, they have greater wear resistance than low carbon steels and some compare favorably with Hadfield's high manganese steel in this respect. Certain low priced and short lived alloys, such as low alloy cast irons, may be listed in this group, but they find only minor application as hard facing materials.

Group 2—This group consists of iron-base alloys with more than 20% of alloying constituents. Various amounts of chromium, tungsten, manganese, silicon, carbon, and sometimes cobalt, nickel and other elements are contained in these alloys. Naturally these hard metals are higher priced than those of lower alloy included in Group 1. However, they are harder, possess greater abrasion resistance and give longer service. As a rule they are not as shock resistant or tough as Group 1, but are particularly adapted for use as the final wear resisting surface, after the worn part is built up with high strength welding rod. Due to longer life of these metals, they frequently are more economical than cheaper metals.

Group 3—Nonferrous alloys of cobalt, chromium and tungsten make up this group. They are available in several different grades, all highly resistant to wear and corrosion, but having a spread in strength and toughness which makes them suitable for a wide range of hard facing applications. Because of their higher melting points these alloys have the property of red hardness, that is, they retain their original hardness practically unimpaired at elevated temperatures.

Group 4—The fourth group consists of the so-called diamond substitutes, the hardest and most wear resistant of all hard facing materials. Some of these are almost pure fused tungsten carbides, containing only fractional percentages of alloying constituents. Others contain 90-95% tungsten carbides, the remainder being cobalt, nickel, iron or similar elements. Other materials may contain boron compounds or tantalum carbide.

The alloys are added to impart toughness and impact strength to the tungsten carbides, the hardness of which, however, is slightly reduced as a result.

These diamond substitutes are furnished in the form of small castings, which are welded and imbedded into the cutting and wearing surfaces of oil well drilling bits and similar tools. Tungsten carbide inserts are not melted or damaged to any appreciable extent in the usual method of applying them by the oxy-acetylene process. The process of applying tungsten carbide shapes to wearing surfaces is

*Compiled and arranged by C. W. Obert, Sr., Union Carbide and Carbon Corp., from the pamphlet published by the International Acetylene Association entitled "Hard Facing by the Oxy-Acetylene Process". Reviewed and supplemented by several individuals in the electric arc welding industry.

known as "hard setting." After hard setting, the wearing surface usually is hard faced. This combination affords an excellent abrasion resisting surface with maximum cutting qualities at edges.

Group 5—Crushed tungsten carbides of various screen sizes comprise the fifth and last group. These are furnished packed in steel tubes of various diameters, fused to steel strips, or bonded with steel in the form of a composite rod. Both tubes and strips come in short lengths, which are applied like ordinary welding rods. Crushed tungsten carbides are also supplied loose, in granular or powdered form, to be sprinkled directly onto the wearing surface and melted into it. These types are more costly than the best of the hard facing alloys but this is more than offset by their much longer life on applications where wearing surfaces of composite nature are to be preferred.

Selection of Hard Facing Alloys—In order to select the correct hard facing material for any particular application, the user should first determine those factors which cause the deterioration of the wearing part. In general, the attack on the part will involve one or more of the following: Sliding or rolling friction, shock and impact, heat, and corrosion. Other factors, such as smoothness of the deposit desired, or, in handling sand, rock and gravel, the ability of the hard faced part to form an efficient digging tool, also affect the choice. The cost factor should also be considered, as a general rule, when two materials are equally suited, the material giving the longer life although more expensive will more than justify its greater first cost.

When the factors have been determined, the following table should serve as a fair guide in the selection of the proper material. The numbers refer to the five groups of materials described above.

Table I
Relative Characteristics of Hard Facing Deposits

Characteristic of Deposit	Group Number in Order of Preference
Cold hardness	4 5 2 3 1
Red hardness	4 5 3 2 1
Resistance to impact	1 2 3 5 4
Corrosion resistance	3 2 1 4 5
Smoothness of deposit	3 1 2 5 4
Ability to take high finish	3 2 1 4 5
Ability to penetrate (earth boring or penetrating tools).....	4 5 3 2 1
Thinness of deposited layer welding.....	3 2 1 5 4

Hard Facing Procedure—Although hard facing materials can be applied by any of the standard fusion welding methods, there are several factors which govern the choice of method for any particular application, such as: 1. Material to be faced; 2. Kind of hard facing material selected; 3. Size, shape and thickness of base material and deposited facing material; 4. Initial cost of equipment and facing material for each process; 5. Smoothness of deposits; 6. Overall cost; and 7. Quality and appearance of deposits.

Gas Welding—The oxy-acetylene blowpipe or torch allows close control over the operation and produces a smooth deposit. Particles of scale and foreign matter are easily eliminated by this method, and edges and corners may be readily formed. This is particularly important where it is later necessary to grind the hard facing to close tolerances. Other advantages are the elimination of any loss of expensive alloys by vaporization or spattering, close control of the oxidizing or reducing conditions of the atmosphere surrounding the molten metal, and more accurate control over the degree of penetration of hard facing alloy in the base metal. The latter is of importance especially with respect to the application of certain classes of hard facing materials, some of which should be puddled in, while others are flowed onto the base material at a "sweating" heat. The oxy-acetylene process offers the facilities for producing either condition at the will of the operator.

Metallic Arc Welding—In metallic arc welding, a metallic alloy rod constitutes both electrode and hard facing material. The electrode is usually flux coated instead of bare. The function of the coating is to stabilize the arc, control the melting rate of the electrode, protect the molten metal from contamination by atmospheric elements and in some cases add alloys to the deposit. While not as flexible as the gas welding process the resultant deposits are equal in quality.

With electric arc welding, experience has shown that in most cases, when the area to be surfaced is large, the most practical and efficient method of deposition is through the use of a weaving bead type of deposit, as distinguished from the straight bead type. This requires the deposition of a bead from $\frac{1}{4}$ -2 in. in width. A deposit of this type can be laid down of a uniform thickness and leave a smooth and regular surface.

Narrow beads are readily applied to corners and edges and for building up points. As it is natural that the edges of such deposits tend to be rounded, it is obvious that this can be offset by the use of double beads, or backing-up strips or jigs of graphite, carbon paste or copper.

Beading is sometimes used when covering large areas and under such conditions the beads should be staggered over the entire area and then tied in together. This method of deposition will give an even distribution of heat and will minimize the strain in cooling. For such applications preheating is generally unnecessary unless the surfaces to be covered are round, curved, concave or convex, in which case it is desirable to preheat. The thickness of the deposit depends, with electric arc welding, upon the heat used and the amount of build-up behind the crater. Normally this will range from $\frac{1}{4}$ - $\frac{5}{32}$ in. In some cases heavier deposit layers can be built up if the work can be placed on a slant of about 15° from the horizontal. On the other hand, thinner deposits can be laid down by moving the electrode over the work more rapidly.

The metallic arc welding process is particularly suitable for hard facing at low cost, thick base metals where exceptionally thin smooth deposits are not required. Distortion is also reduced when hard facing large steel castings and similar heavy parts by this process since the heat from the arc is well localized.

Atomic Hydrogen Arc Welding—In the atomic hydrogen arc welding process an alternating current arc between two tungsten electrodes in a stream of hydrogen gas furnishes the source of heat. The arc is surrounded by an envelope of hydrogen gas which protects the electrodes and work from oxidation. The arc is defined by a thin brilliant line which forms a loop under the influence of its own magnetic field and the streaming gas.

This process gives high quality of deposits plus all of the other advantages outlined for hard facing using the gas process. In addition, since the atomic hydrogen arc has a higher temperature and the heat is concentrated over a smaller area a higher deposition rate may be obtained. The initial cost for atomic hydrogen equipment is often more than offset by the speed and results obtained on many hard facing applications.

Materials Which Can Be Hard Faced—The following classification affords a ready means of determining what metals or alloys can or cannot be hard faced.

Medium and Low Carbon Steels—All carbon steels up to 0.50% carbon can be hard faced with perfect results in practically all instances. Such steels, especially in the 0.40-0.50% carbon range, are not only satisfactory from the viewpoint of the welding, but also have sufficient strength to stand up well under severe operating conditions.

High Carbon Steels—Steels containing above 0.50% carbon can be hard faced if reasonable precautions are taken to prevent the steel from cracking. It is often desirable to preheat such high carbon steels before hard surfacing. In most cases, heat treatment is necessary to remove hardness and brittleness from the base metal both before and after hard facing.

Low Alloy Steels—Hard facing alloys can be applied to low alloy steels in much the same manner as to plain carbon steels. Such material should be in the annealed condition before welding. In a few cases, depending upon the composition of the base metal, heat treatment is required after welding.

High Speed Steels—The hard facing of high speed steels is not generally recommended, because shrinkage cracks and strain checks render the hard faced piece valueless in a good many instances, regardless of heat treatment.

Stainless Steels—Stainless steels, including the high chromium steels and the 18-8 chromium-nickel steels can readily be hard faced if proper preheating and cooling procedures are followed. However, a knowledge of the physical properties of the particular type of stainless steel is necessary, otherwise difficulty may be experienced due to excessive strains, brittleness, or lessened corrosion resistance.

Manganese Steel (9½-14% Mn)—This class of steels can be surfaced to advantage by use of a rod that gives an austenitic, work hardening deposit. Man-

ganese steel should always be hard faced by the electric arc welding process, with care being taken to avoid overheating.

Gray Cast Iron—Cast iron can be hard faced easily, but the method of application is somewhat different from that for steel due to the lower melting point of the cast iron and the crust formation on the surface of the iron. Care should be taken not to develop localized overheating of the iron.

White Cast Iron—White or chilled iron can be easily hard faced in small parts; on larger parts heat treatment is sometimes necessary and a careful study of the design and location of chills is necessary, since preheating may soften some of the chilled areas.

Alloy Cast Irons—The same procedure can be used as for hard facing gray cast iron.

Monel Metal—Monel metal is easily hard faced.

Brass and Bronze—These copper-base alloys are difficult to hard face because of their low melting point. In rare instances, however, heavy sections which have been preheated to a red heat can be hard faced.

Copper and Copper Alloys—Because of its low melting point and high heat conductivity, copper is hard faced only with difficulty. Preheating is absolutely necessary.

Preparation of Work—All loose scale, dirt, rust, or other foreign substances should be removed from the areas to be hard faced, preferably by grinding or machining. If these facilities are not available, the surface may be cleaned with a file or wire brush, but this method often leaves scale or other foreign material which must later be floated out during the hard facing operation.

Where the hard facing material is to be applied to a groove, corner or recess, it is preferable to have all corners well rounded, otherwise overheating of the base metal may result. If but a small section of a part is to be hard faced, a suitable shallow recess or indentation to receive the hard facing metal may be prepared either mechanically or with the blowpipe or torch.

Preheating—The same general rules apply to preheating before hard facing as apply to most welding operations. Parts are always preheated in cases where the application of the hard facing alloy would otherwise cause them to warp or check, or where time and cost can be saved by preheating. Steels having over 0.40% carbon should usually be preheated. The optimum temperature of preheating is dependent upon the size and composition of the part, but usually it is between 700-1200°F. For certain classes of electric arc welding a preheat of from 350-450°F. is desirable.

It is generally unsatisfactory to hard face steels which are in a hardened state. If it is necessary or desirable to reharden the base material after the hard facing has been applied, it should be quenched in oil (water quenching is seldom used because it tends to crack many hard facing materials).

Fluxes—In the gas or atomic hydrogen welding process, fluxes are not ordinarily essential except in special instances. Sometimes a flux is of assistance where a second layer of hard facing is necessary, or to help remove scale and oxide from the base metal. This is especially true with cast iron. The principal advantage of a flux is that it floats on the molten puddle of deposited material, smoothing its surface and retarding the cooling action as well as protecting the metal from oxidation. In addition, a denser, harder deposit of superior microstructure is produced if a flux is used. No flux is required in shielded electric arc welding in addition to that processed on the electrode itself.

Thickness of Hard Facing Deposit—In the vast majority of cases, hard facing deposits range from $\frac{1}{8}$ - $\frac{1}{4}$ in. in thickness. The average is approximately $\frac{1}{8}$ in., but the proper thickness depends entirely upon the specific application. However, parts requiring a deposit thicker than $\frac{1}{4}$ in. are usually rebuilt, before hard facing, with one of the alloys of Group 1, or with the material of which the base metal is composed, to within $\frac{1}{8}$ - $\frac{1}{4}$ in. of the finished size. The final hard facing deposit is applied to a thickness allowing sufficient metal for grinding to finish size.

Hard Facing Steel—Group 1. Iron Base—Less than 20% Alloy—In applying hard facing welding rods of Group 1 to steel, a flame containing a slight excess of acetylene should be used, since a neutral flame may cause boiling and sometimes produces an unsatisfactory result. Penetration of the hard facing alloy in the base metal should be from 0- $\frac{1}{2}$ in., depending on the type of rod used. Some of these

materials are work hardening, and light peening is recommended, especially on large areas, both to harden the surface and to eliminate the danger of shrinkage cracks.

The hardness of deposited hard facing metals of this class depends largely in the case of gas welding upon the amount of acetylene used in the flame and upon the rate of cooling; a small excess of acetylene is usually necessary to prevent the rod from boiling. A much greater excess can be used if an exceptionally hard deposit is desired. In general, it may be said that the greater the excess of acetylene and the slower the rate of cooling the harder the deposit will be. A quenched deposit is not as hard as, but is tougher than, slowly cooled metal.

With electric arc welding, electrodes are available which will give a medium carbon alloy steel facing. With most of such electrodes the rod should be positive and the work negative. The welding current should be adjusted to give flat beads such as are generally produced with high currents, and the deposit should be made with a weaving motion where possible. For this class of work welding should be done in a flat position only.

Group 2. Iron Base—20-50% Alloy—It is generally recommended that alloys of this group be applied to steel by thorough amalgamation. In the case of gas welding, a neutral or slightly carburizing flame is generally used. To assure successful hard facing, melting of the base metal should actually take place; sweating is not advisable. Since the hardness and other physical properties of these alloys remain practically unchanged within a carbon content range of from 2-4%, penetration of the base metal has no marked effect on the quality of the deposit.

With electric arc welding electrodes are available that will produce a high carbon steel facing that is hard and cannot be machined unless annealed. For most of such electrodes the rod should be positive and the work negative. Wide or narrow beads can be deposited as desired. Each bead should be brushed thoroughly before depositing the next, and, in some cases, peening the completed bead will harden the deposit. Quenching in cool water will increase the surface hardening of some types of this group. For best results the work should be in as nearly a flat position as possible.

Group 3. Nonferrous Cobalt-Chromium-Tungsten Alloys—The nonferrous alloys should be applied, when possible, without penetration into the steel base metal. In this manner, it is possible to avoid dilution with iron of the base metal and thus preserve the red hardness and abrasion resisting properties of the alloys. With gas welding, the flame for hard facing with the nonferrous alloys must contain an excess of acetylene and should be adjusted so that the flare or outer cone denoting an excess of acetylene extends double the length of the inner cone. This amount of excess acetylene will make the surface of the steel base metal "sweat," allowing free spread of the hard facing metal without any stirring or agitation of the puddle by the rod.

A small area of the surface to be hard faced should be brought to a sweating temperature, and the end of the rod brought into the flame and allowed to melt and spread evenly over the sweating area. The hard facing material, when applied at the proper temperature, wets the base metal and spreads readily ahead in the flame as the flame brings the base metal to the sweating heat just ahead of the puddle. The rod should not be stirred or puddled. Additional alloy is spread in the desired direction by means of the welding flame.

It is usually possible and preferable to build up the coating to the desired thickness in one operation. As a general rule, no flux is necessary when the nonferrous alloys are applied to clean steel.

The alloys in this group can be applied by the metallic arc process either bare or flux coated, preferably coated. Reverse polarity is always used, making the rod positive and the work negative.

Group 4. Tungsten Carbide Inserts—Tungsten carbide inserts are now in almost universal use for hard setting oil well drilling tools. In general, the procedure involves, first, cutting grooves in the steel base metal by means of either an oxy-acetylene cutting blowpipe or a grinding wheel. The size and spacing of the inserts will vary with the type of drilling tool. The steel in one groove should be melted with an excess acetylene flame. One insert should then be picked up with the heated end of a high strength steel welding rod and partially submerged in the molten puddle. Finally the insert should be completely covered over with the steel welding rod. This operation is repeated until the desired number of inserts have been set. Maximum wear resistance is obtained when a final coating of hard facing alloys of Group 5 is deposited over the inserts.

Group 5. Crushed Tungsten Carbide with Steel Binder—These materials consist essentially of two types—composite and tube; both are applied in much the same manner. The operation should be performed with the oxy-acetylene process, using a flame containing a small excess of acetylene. The application should be made without penetrating as deeply into the base metal as in ordinary steel welding. A certain amount of stirring with the rod is necessary to obtain the most even distribution of the deposited metal. These rods do not flow as freely as most ordinary welding rods, due to the presence of the refractory tungsten carbide particles which are not melted during the application. It is best to avoid keeping the deposit molten for too long a period. The welding tip should be large enough to produce a flame which will supply the required amount of heat with the pressure low enough to avoid blowing the molten metal.

Hard Facing Cast Iron—Group 1. Iron Base—Less than 20% Alloy—In applying materials of this group to cast iron, a small area at a time should be heated with the blowpipe, and the surface crust broken with the end of the rod. A little puddling is usually necessary and a good flux is often helpful. Because of the low melting point of cast iron, considerable care should be taken when working up thin surfaces, edges, and corners. Other than this, hard facing cast iron with the materials of Group 1 is similar to hard facing steel.

Group 2. Iron Base—20-50% Alloy—These alloys are applied to cast iron in essentially the same manner as they are applied to steel.

Group 3. Nonferrous Cobalt-Chromium-Tungsten Alloys—These alloys when gas welding is used should be applied to cast iron with a little less acetylene in the flame than is used for steel. Since they do not flow as readily on cast iron as on steel, it is usually necessary to break the surface crust with the end of the rod. A cast iron welding flux is often helpful. It is usually best to weld in a thin coating first and then go over it again and build up to the desired thickness. These alloys have approximately the same melting point as cast iron, and care must be taken not to melt the base metal too deeply. If the cast iron is thin, it will prove advantageous to back it up with wet asbestos or carbon paste to avoid melting it.

Groups 4 and 5. Tungsten Carbide Inserts and Rods—These hard facing materials are rarely, if ever, applied to cast iron in practice. In those few instances where they are, the technique follows generally along the same lines as the procedure for their application to steel.

Cooling Procedure—Most satisfactory results are obtained after hard facing by the oxy-acetylene process if the part is cooled slowly to avoid setting up stresses in the deposited metal. A little more care is necessary than is employed when the base metal and welding rod are of the same composition. If no further heat treatment is necessary, the hard faced piece may be cooled under the blowpipe or torch, or can be cooled in dry lime, sand or other packing material. If, however, the piece is to be heat treated to improve the strength of the base metal, and to produce a finer and stronger grain structure, the hard faced piece should be heated and then either quenched in oil (seldom water) or normalized by cooling in air.

Finishing the Hard Faced Deposit—Groups 1 and 2. Iron Base Alloys—These hard facing materials may be shaped to a certain degree while they are in their plastic temperature range. When a deposit of one of these alloys is heated with the blowpipe to within 200-300°F. of its melting point, it may be scraped off in thin layers with an implement, such as an old file, until the deposit has been brought down to the required size and shape. Ordinarily, alloys of Groups 1 and 2 are difficult to machine. If they cannot be brought down to their finish dimensions exactly by "hot filing," as this procedure is known, grinding is necessary.

Group 3. Nonferrous Alloys—Most grades of the nonferrous hard facing materials are too hard to be machined or filed, but they can easily be finished by grinding. The wheel speed when grinding these alloys should not be less than 2,800 nor more than 4,200 surface f.p.m. Higher speeds or wheels that are too hard may cause grinding checks.

Groups 4 and 5. Tungsten Carbide Inserts and Rods—The best results in grinding parts hard faced with these materials will be obtained by using wheels designed for this particular work. Grinding wheel manufacturers should be consulted and their recommendations followed as to proper grade, grain and bond. All wheels should be kept sharp by frequent dressing to avoid glazing and checking of the hard faced surfaces.

Bond Between Hard Facing Material and Base Metal—The bond obtained between the hard facing material and the base metal is as strong and sometimes even stronger than the hard facing deposit itself. Naturally, those alloys which are puddled into the base metal form a good strong bond. Those alloys which are merely sweated to the base metal, actually form a bond which is stronger than the hard facing metal itself. If properly applied hard facing metals do not break away from the base metal at the bond.

On many hard facing applications, surface cracks are not detrimental since they usually run only through the deposited metal and stop at the base metal. If surface cracks are present and undesirable, they can sometimes be repaired by heating the metal adjacent to the crack to a red heat, then melting down into the bottom of the crack and allowing it to close in slowly, meanwhile adding a few more drops from the welding rod. The heat should be drawn slowly away from the hot spot into the body of the base metal to prevent quick cooling and subsequent cracking and the part should be cooled slowly in lime, sand, or mica.

Drawing-Out Rod—When rods smaller than $\frac{1}{4}$ in. dia. are required for application to small parts, it is possible and often desirable to "draw-out" $\frac{3}{8}$ or $\frac{1}{2}$ in. dia. hard facing welding rod to roughly $\frac{1}{4}$ or $\frac{3}{8}$ in. dia. This procedure applies primarily to those hard facing alloys of Group 3. Some operators prefer this practice while others prefer to buy the smaller diameter rods ready for use. Depending on individual shop conditions, including local costs for material and labor, one method or the other may be the more economical.

The actual drawing-out operation consists of melting one end of the large diameter rod with the usual excess acetylene flame. The first drop of molten rod is laid on a cold plate of carbon, graphite, iron or steel. With the welding flame playing steadily on the end of the rod and melting it, the rod is drawn away from the initial drop at a steady rate, leaving a thinner rod deposited on the plate. Angle iron or a grooved plate is generally preferred to a flat plate, since these give more uniform shape to the "drawn-out" rod. At the completion of the "drawing-out" operation the newly formed small rod is ready for use.

Jigs for Hard Facing—Many hard facing operations, both in production and repair, are facilitated by devices for holding the work and special jigs. Some operations which otherwise might not be practical, can be rapidly and efficiently accomplished through the use of auxiliary appliances. Profits derived from an operation are often greatly increased by the savings in labor, time and handling thus made possible. Several typical examples of jigs will suggest ways of facilitating the hard facing operation.

Several coal companies have found it much easier and faster to hard face undercutter bits when they are set up on a jig. Either a "merry-go-round" jig or a moving table may be employed to good advantage in this application. At one coal company which uses the former method, 450 bits are hard faced by one operator in an hour.

A well designed jig and nose plate help tremendously in obtaining properly shaped plowshares. With the aid of these accessories, a plowshare may be hard faced and its nose shaped in one operation. A further aid in plowshare work is the use of a jig designed to swivel as well as turn the share completely over. A share clamped in such a jig can be readily adjusted so that the area on which the welding operator is working is always level. Rotating jigs or chucks set at a convenient angle are a great aid in hard facing steam valves, dies, automotive valves and valve seat inserts and other small parts. Even simple rests on which the work can be placed are often helpful in allowing the welder to work in a comfortable position. Most jigs are home made affairs, adapted specifically to the jobs in question, and a little ingenuity on the part of the operator will aid him in turning out work more quickly and accurately with greater economy and convenience.

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Rolls for the Metal Industry*

Rolls are used in the metal industry for reducing the cross section of plastic metal or changing its shape or both. As a rule, two rolls are used, running in opposite directions as shown in Fig. 1; the metal to be rolled, which will hereafter be called the bar, no matter what shape it has, passes between the rolls and is therefore reduced in cross section. In cross rolling, Fig. 2, such as used in the making of seamless tubing and straightening rounds, the rolls rotate in the same direction and set a piece of metal in rotation as it passes between them longitudinally.

Roll Parts—A complete roll with roll body, neck, and wobbler is shown in Fig. 3. The roll body or roll face is the working part in contact with the bar to be rolled. The roll neck is that part which lies in the bearing or journal box. The wobbler is that part which receives the torque from the outside source of power. Instead of wobblers, some rolls are equipped with universal joints, Fig. 4, which make contact on surfaces rather than lines or points and thereby minimize wear.

Roll Types and Arrangement in Roll Housing—"Blooming mill" rolls convert ingots into blooms.

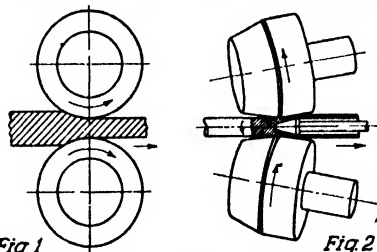


Fig. 1—Illustration of rolling.

Fig. 2—Cross rolling.

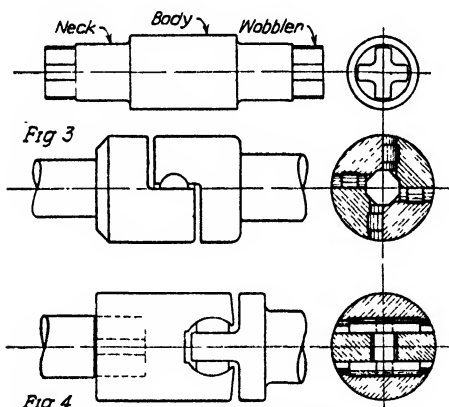


Fig. 3—Complete roll with roll body, neck, and wobbler.

Fig. 4—Universal joints for rolls.

"Roughing" rolls are used in the early stages of reducing billets and blooms into various shapes.

"Intermediate" rolls, also known as "second roughing," "pony roughing" or "strand" rolls work on the bar after it comes from the roughing rolls.

"Leader" rolls are those preceding the finishing stand.

"Finishing" rolls or "planishing" rolls in the case of flat products are used to give the bar its final shape.

If only two rolls are used in a mill, the latter is called a two-high mill. If three rolls are used, (usually on top of each other) the mill is called three-high, and so on. Not all rolls are in contact with the material to be deformed. Some rolls act as stiffening or supporting rolls for smaller rolls which are in contact with the work. The latter are called working rolls while the former are called backing rolls. Fig. 5 shows the arrangement of rolls on three-high, four-high, and cluster mills.

Roll Requirements—Wear resistance is the first requirement for rolls since rapid wear of rolls impairs the surface or enlarges the section beyond the tolerance which can be used. Wear is caused by the relative motion between the bar and the roll surface. In all rolling there is relative motion between rolls and bar while roll and bar are pressed against each other at enormous pressures, which, in severe cases, reach several hundred thousand psi. Hardness is regarded as being a general guide to wear resistance, although it is not an infallible index. The roll hardness is usually determined by the Shore scleroscope because of the portability and fair reproducibility of results with this instrument. Hardness, and consequently wear resistance, of a roll is limited by the strength requirements since ductility and shock resistance decrease as the hardness increases.

*Prepared by the A.S.M. Subcommittee on Rolls. The membership of the subcommittee was as follows: S. C. Spalding, Chairman; F. H. Allison, Jr., W. P. Goss, E. H. Berges, A. L. Davis, W. Trinks, G. J. Buckner, J. R. Adams, J. T. Haight, Harry Jenter, V. M. Surerus, and F. C. T. Daniels.

Strength is necessary for the rolls to withstand fracture from bending, torsional, and shearing stresses to which they are subjected in operation. Sufficient strength for any application depends upon the chemical composition of the roll, the heat treatment, and the freedom from strains and internal defects. Initial strains are present to some extent in every roll. Size, thermal treatment, and casting conditions play an important part in these strains. Under service conditions, rolls which have high internal strains may rupture easily by uneven or rapid heating on the mill. This is particularly true of chilled iron rolls for sheet mills. Strength is necessary to resist spalling which frequently originates below the surface and progresses outward until the part breaks loose. Thus subsurface strength and hardness are required to keep spalling at a minimum.

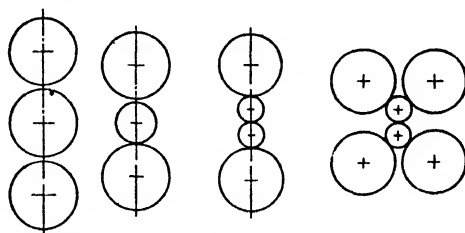


Fig. 5—Arrangement of rolls on 3-high, 4-high, and cluster mills.

Bite is necessary for grabbing the metal and starting it through the roll. It depends partly upon the roughness of the roll surface. Bite is particularly important in taking large reductions, and in many blooming or roughing mills the surface roughness is artificially increased by ragging or knurling. This is done by cutting longitudinal grooves or welding ridges on the roll surface. Ragging must be applied with care or it will show in the finished bar. Where reductions are small as in the leader and finishing pass, a smoother roll can be used.

Surface perfection (quality) of the roll is necessary to obtain a good bar. In cold rolling where surface finish of the product is of great importance the roll surface must be ground to a high finish and be exceptionally free from defects. Only the highest hardness will preserve such a surface for a sufficiently long commercial operation. In hot rolling, the roll surface is subjected to fire cracking by alternate contact with the hot bar and the cooling water. Fire cracking is greater in the early passes where the hotter metal and larger reductions prevail. Both fire cracking and spalling which ruin the surface of the rolls are associated with roll strength.

The surface must be metallurgically correct. If the bar material has too great an affinity for the roll metal, it sticks to it and "loads" the roll. The solution to this problem is not always easy. Change of roll material helps in some cases; insertion of a lubricant between roll and bar helps in others; insertion of another metal between roll and bar has become necessary in a few cases.

Rigidity in a roll is essential to reduce the deflection or roll spring across the roll length. This is particularly important in rolling flat products such as plate, sheet, or strip. If the rolls spring, the edge of the section is wavy and thinner than the center. For a given diameter a steel roll is more rigid than a cast iron roll, but the hardness of the steel roll has no effect on its rigidity since deflections depend solely on the modulus of elasticity which is the same for hard steel and for soft steel. Leader and finishing rolls are made relatively short for the purpose of reducing roll spring and giving true finished dimensions. Crowning the roll will produce a flat section by making the diameter slightly larger at the center than at the ends, but crowning is a limited remedy since a given crown can be correct for only one thickness, hardness, and width of section.

Roll Size and Design—The size of a roll is specified by the diameter and the length in the order named, such as 24 x 48 in. Rolls for shapes are often designated by the nominal roll or pitch diameter, which equals the distance between the centers of the mill driving pinions. The diameter of the rolls is usually smaller than the pitch diameter because there must be room for the passing of the bar between them. Occasionally the roll diameter is larger than the pitch diameter when the rolls are new. Plain rolls, used for plates and strips, may sometimes be designated by the length of the roll body. Rolls of the smallest possible diameter are used as far as it is consistent with strength, bite, and rigidity because rolls of relatively larger diameter tend to spread the bar, cause greater roll pressure or separating force and use more power for a given reduction. Rolls are made as long as is consistent with safety against breaking by bending. The deeper grooves of grooved rolls are placed as far as possible from the center in a location where the bending moment is smaller.

For grooved rolls, a three to one ratio of body length to diameter is small while a four to one ratio is large. Smaller ratios, such as one and a half to one are used for leaders and finishers where deflection must be a minimum.

Fairly sharp limitations exist as to the largest size section that can be rolled on any mill because above a certain section the rolls do not bite, or break in bending, the wobblers twist off, the necks overheat, or the mill is stalled.

The sudden change of diameter from roll body to roll neck intensifies the bending and torsion stress at this location. The neck diameter should not be smaller than a certain safe fraction to the body diameter, which with plain bearings will average about the following:

Type of Mill	Ratio	Neck Diameter
		Body Diameter
Blooming mills		0.50-0.55
Sheet mills and tin mills.....		0.76-0.80
Strip mill, backing rolls.....		0.55-0.65
Strip mill, working rolls.....		0.60-0.65
Merchant bar mill.....		0.60-0.67
Plate mill, middle roll.....		0.60-0.70
Plate mill, top and bottom rolls.....		0.65-0.72
Structural mill		0.57-0.65
Continuous bar mill.....		0.70
Universal mill, vertical rolls.....		0.57
Cold rolling brass, heavy reduction.....		0.775
Cold rolling brass, finishing reduction		0.72-0.75

Misuse—Rolls can easily be broken or damaged by misuse. In hot rolling, the entering bar may be too cold or unevenly heated. Fire cracking usually occurs if the mill is stopped while the hot metal is between the rolls. The bar may run between the collars instead of entering the groove whereby the roll pressure becomes excessive. Strips or bars may by accident wrap around the roll, forming collars and inducing excessive stresses in the rolls. Lubrication may stop in cold rolling. Other events may occur on the mills which overstress the rolls and contribute to failure some time after the event. Among them are local heating, too rapid heating, too rapid cooling, bruises, and nonuniform cooling.

Forged Steel Rolls—There are special types of forged rolls made for specific applications but by far the greatest number are used for the cold rolling of metals and are of a generally standardized composition and finish. The average composition is as follows: C 0.85, Si 0.30, Mn 0.30, Cr 2.00, and Ni, V, or Mo may be added either singly or in combination.

Manufacture—Forged steel rolls are made from acid open hearth or electric furnace steel cast in ingot molds of suitable size and shape to afford the required reduction in forging to produce the necessary structure and grain refinement. After forging, the roll is put through suitable normalizing and annealing processes, after which it is rough machined to size and heat treated. The roll is then machined for hardening and hardened by heating to proper temperature and quenched in water or brine with special fixtures and devices to insure extreme hardness on the working face and prevent or retard hardening of necks, shoulders, fillets, and so forth. After hardening the roll is tempered to relieve strains and to obtain the desired hardness.

The roll is given a preliminary test for hardness. The customary test for hardness of rolls is the scleroscope. The next step is machining and grinding to finished dimensions and desired surface finish. Forged steel rolls are capable of a high surface finish. For special purposes a so-called "mirror finish" may be put on the rolls.

Application—This type of roll is used for cold rolling and for the finishing of thin metal where a high grade finish is desired. The hardness is varied with the service for which the roll is intended. For extreme hardness and fine finishing thin metals a hardness of greater than 95 scleroscope is usually used. For soft and thicker metal such as running down or semifinishing, a hardness of 80-90 scleroscope may be used. For heavy roughing and special purpose, hardnesses less than 80 scleroscope are used.

When forged rolls are used as backing-up rolls in 4-high mills, the scleroscopic hardness is dependent on sizes of roll and character of mill. For the small strip or band mill, the hardness should be 75-90 scleroscope. For the larger diameter forged backing-up rolls used in either hot or cold strip mills, the hardness should be within 55-80 in order to insure the maximum service possibilities. Forged rolls are applied

as backing-up rolls when high pressures are used and high strength required. Forged steel rolls of various hardnesses are used for many auxiliary purposes around mills, such as leveller rolls, pinch rolls, colling rolls, and carrier rolls.

The extremely hard rolls must be handled with great care and precautions taken in use to prevent them from being subjected to rapid changes in temperature. Before rolls are put into service they should be preheated to approximately rolling temperature preferably by means of heated water or low pressure steam in the bore. Preheating of rolls by means of a gas flame is dangerous and should never be used unless rolls are rotating. Rolls should never be warmed up by running them in contact with each other. Idling the rolls in contact with each other for any reason is dangerous. This practice may cause minute surface fractures that ultimately result in a spall. When not rolling, the rolls should be separated from each other and the cooling water immediately turned off whether they are rotating or not. Rapid and excessive heating of roll journals from defective bearings or improper lubrication, causing rapid local expansion or subsequent rapid contraction, will result in a broken or spalled roll or fire cracked journal.

Bruises on the faces of rolls frequently bring about spalling. Bruises often result from the ends of the strip being harder than the rest of the strip, from badly sheared ends, turned over or broken edges, pinches due to improper roll shape, or mill setup, nonuniform thickness of strip or sheets, passage of foreign material such as micrometers, or small spalls from backing-up rolls. Whenever a roll is bruised it should be ground until no trace of the spall remains after polishing and etching with a solution of ethyl alcohol containing 7% of nitric acid.

Forged steel rolls can be readily damaged by improper grinding. For roughing down and rough grinding coarse free-cutting wheels are essential. Fineness of grit for finish grinding and polishing depends on the finish required. The selection of the proper bond and hardness and adoption of correct roll and wheel speeds is necessary or injury to the face of the rolls will result. The grinding wheel manufacturer should be consulted when selecting the proper wheels for the condition that obtains in a shop.

Hardened steel rolls should be stored in a dry room kept at a reasonably constant temperature. They should be well slushed to prevent rusting. They are best supported on their journals. The forged steel roll makers customarily furnish instructions and precautions for the care and use of their rolls.

Cast Rolls—Cast rolls may be divided into two classes, (1) Cast iron rolls and (2) Cast steel rolls.

Cast Iron Rolls—Cast iron rolls in American practice are subdivided into three classifications: (a) chilled iron rolls with a definite chill; (b) chilled iron rolls with an indefinite chill; and (c) sand iron rolls.

(a) *Definite chilled iron rolls* (scleroscope hardness range 55-90) are those rolls having a definitely formed clear homogeneous chilled white iron surface of the body of the roll with a fairly sharp line of demarcation between the chilled surface and the gray iron central portion of the body. The depth of chill is measured as the distance between the finished diameter of the body and the depth at which the first graphitic specks appear. Below this there is an area consisting of a mixture of white and gray iron known as mottle, which gradually becomes more gray and more graphitic until it merges with the grey iron structure of the main part of the roll. The mottled area should be equal or somewhat less than that of the primary chill.

The definite chilled rolls are again subdivided into plain carbon and alloy rolls, the former having a hardness range from 55-72 scleroscope and were the standard rolls in use for both hot and cold rolling until the introduction of the alloy chilled roll. The average composition of carbon chilled rolls is as follows:

	C	Si, min.	Mn, max.	P, max.	S, max.
Soft	3.00	0.75	0.25	0.50	0.125
Hard	3.50	0.50	0.20	0.50	0.150

The alloy definite chilled rolls have a hardness range from 60-90 scleroscope as controlled by the carbon and alloy content. Their composition is essentially that of the carbon roll to which are added one or more special alloys. The maximum percentage of individual alloys used are: molybdenum 1.25, chromium 1.00, nickel 5.5, tungsten 1.5, vanadium 0.25. There are many varying combinations to effect the

properties desired. This type of roll is mostly used in rolling flat work, both hot and cold, particularly in the harder grades. Often the softer, machinable grades are used for small shapes and rod mill work.

(b) *Indefinite chilled iron rolls* are the American "grain" rolls (scleroscope hardness 40-90). They have an outer chilled face on the body but have no definitely formed chilled structure. Finely divided graphite is present at the surface which gradually increases in size with a corresponding decrease in hardness as the distance from the surface increases. This diminution of properties is gradual and these rolls present good wear and finishing qualities to considerable depths. The harder grades are used for hot and cold flat finishing work and the milder grades for deep sections, even with small rolls. The basis of the manufacture of indefinite chilled rolls is low phosphorus pig iron, together with at least 0.75% chromium and up to 2.50%. Other alloys such as nickel and molybdenum are usually added, singly or in combination, to develop specific properties of hardness and toughness such as are shown in the above definite chilled rolls.

(c) *Sand Iron Rolls* (scleroscope hardness 35-45) are those cast in sand molds in contrast to (a) and (b), which have the body cast in chilled molds. The metal in the grooves of the body is refined or densified by the use of cast iron rings set in the sand mold. Sand iron rolls are mostly used for intermediate and finishing stands on shape work but they are comparatively soft and their use is only justified in standard practice when there is insufficient tonnage available to warrant the use of the better and more expensive rolls which are available in the trade.

Manufacture—In the manufacture of definite chilled iron rolls, warm blast charcoal pig iron and worn out chilled iron rolls are used. Low phosphorus pig iron and worn out "grain" rolls are the basis of the indefinite chilled rolls. Both types are usually melted in a reverberatory or air furnace, similar to that used for the melting of iron for malleable castings (see "Malleable Iron," page 641).

When the furnace charge has melted and the bath formed made sufficiently hot a preliminary test is taken and cast in a sand mold, one side of which is a cast iron block to act as a chiller. The test is cooled, broken, and the fracture observed for the depth of chill. The chill on this test corresponds proportionally to that which will be found on the roll itself. A chemical analysis is usually made to check the physical readings and often a second test block is made to also check the first readings and stability of the bath. Should the readings show the depth to be either slightly shallower or deeper than that required, it may be increased by the use of sulphur, chromium, or low silicon white pig iron, or decreased with an addition of ferrosilicon, ferromanganese or high silicon graphitic pig iron. When the depth of chill and the temperature is judged to be correct the furnace is tapped into a lip ladle, which is then skimmed to clear the surface of accumulated dirt and slag. The metal is further held in the ladle until it has cooled to the proper temperature before casting. The mold for the roll casting is erected in a perpendicular position. The design of the mold is such that when the metal is poured a rapid centrifugal motion or "swirl" is produced as the metal rises in the mold, thus keeping the surface of the body clean. The heavy cast iron cylinder which comprises the body of the mold conducts heat rapidly from the molten metal, causing the formation of a hard white, or chilled iron surface layer on the body of the roll. The depth of this chill is controlled by the composition of the iron and it is varied to suit the requirements of the roll. The roll casting is allowed to remain in the mold for a period of 12 hr. to 6 days, depending upon its size. Some special alloy castings are taken out of the mold while still quite hot and transferred to an annealing furnace in order to control the cooling rate, or to be reheated to produce certain physical properties.

Application—Cast iron rolls have a wide range of application as they have a superior wearing and finishing quality over other types of rolls of equivalent hardness. They are almost universally used for hot rolling of flat work, such as two-high mills for sheet and tin rolling.

Opinions vary with reference to the application of cast iron, as well as alloy types of rolls, to various mills, due to the differences in mill practices and the varying qualities of finish required. The harder alloy cast steel rolls have an equivalent hardness to the softer cast iron rolls and their superior strength often demands their use. The harder, richly alloyed, definite chilled rolls approach in hardnesses to forged and hardened steel rolls and are competitive with them in the cold finishing of flat work.

Grade	Hardness, Scleroscope	Application
Definite chill (carbon or molybdenum chill)	55-72	Sheet and tin mill hot and cold rolls, 2- and 3-high plate mill rolls, jobbing mill rolls, wet and dry work rolls, 4-high hot strip mills, intermediate and finishing stands, rod, merchant, sheet, bar, skelp mills.
Definite chill (alloy iron)	50-90	Hot and cold nonferrous sheet and strip, 2- and 3-high plate mill rolls, universal mill rolls, work rolls, 4-high hot strip mills, cold rolls, finishing nonferrous and steel sheet.
Indefinite chill (grain alloy)	45-70	<i>Mild Hard</i> Light duty roughing for small merchant, bar mills. <i>Medium Hard</i> Intermediate rolls for merchant and bar and large structural mills. <i>Hard Grade</i> Finishing rolls for merchant, bar and structural mills, also for flat finishing on sheet bar and skelp mills; sizing, high mill, reeler and welding rolls for tube mills.
Indefinite chill (nickel alloy)	65-90	Finishing stands, sheet bar, skelp, strip and merchant mills. Work rolls, 4-high hot strip mills. Finishing nonferrous sheet and strip.
No chill (sand iron)	35-45	Mild duty small mill roughing to large structural finishing.

Cast Steel Rolls—The differentiation between cast iron and cast steel rolls cannot be made strictly on the basis of carbon content. In American practice the division between the two classes is made on the basis that iron rolls are of such compositions as will show apparent free graphite in the unchilled portions and steel rolls do not show graphite.

Composition—A small number of rolls are made from carbon steel, particularly for blooming and billet mills. The carbon range is usually 0.40-0.80% for roughing, and 0.85-1.25% for finishing rolls.

Alloy steel rolls have almost entirely superseded the carbon rolls. The majority of this type will be found within the following percentage range of analyses: Carbon 0.40-2.60, sulphur up to 0.12 usually 0.06% max., phos. up to 0.12 usually 0.06% max., manganese up to 1.25, chromium up to 1.50, nickel up to 1.50, and molybdenum up to 0.60. Lower carbon content gives greater strength while higher carbon affords increased hardness and wear resistance.

There are a small number of rolls made of higher alloy content than above indicated, but these are usually special purpose rolls.

In exceptionally large rolls where casting and heat treatment problems are intensified, or where hard surface and softer strong centers are desired, the roll may be made of an arbor for the center and necks, on which is shrunk a harder sleeve. These are known as "sleeve" rolls. Instead of scrapping solid back-up rolls which have become worn out or for any reason are not fit for mill use, they may be turned down and used for an arbor of a sleeved roll providing the metal is in good condition and sound.

Production—Steel rolls are generally cast from acid open hearth metal, although basic open hearth and electric furnace steel is sometimes used. The steel is cast in a dry sand mold in which suitable metal chills may be placed for more rapid solidification in certain portions of the roll. The mold is cast in a vertical position and the metal enters the bottom neck at an angle to the circumference so as to set up a swirling motion. This swirl carries any loosened sand or dirt to the center of the roll and results in a clean surface. A fairly large head and cope neck is necessary to feed the casting and avoid shrink holes. The cope neck is generally less strong than the drag neck, due both to the greater segregation at the upper portions of the casting and to the removal of more of the condensed surface metal in the enlarged area to reach finished size. After casting, the gates and head are removed from the rolls; it is then annealed or otherwise heat treated, and turned or ground to finished size.

Heat Treatment—Depending upon the service required, the hardness, and the composition, cast steel rolls are generally given one of the following heat treatments:

Single Annealing—Heat above the critical point for grain refinement and

Double Annealing—Heat well above the critical point for homogenizing and grain refinement, followed by heating only slightly above the critical point for further grain refinement.

Normalizing—Cool in air after double annealing to increase strength in special cases.

Rolls are graded by carbon range and general application as follows:

Carbon Range, %	Application
0.50-0.65	Where strength is the prime and only requirement.
0.70-0.85	Blooming mills, jobbing mill, plate mill and sheet mill roughers; muck mills.
0.90-1.05	Blooming mills, continuous bar mill roughers, backing-up rolls.
1.10-1.25	Blooming mills where breakage is not great; piercing mills; billet, bar, rail and structural mill roughers.
1.35-1.55	Rail mill intermediate stands; structural, continuous billet and continuous bar mills.
1.60-1.80	Continuous bar and billet mill intermediate stands; 3-high mill middle rolls.
1.85-2.05	Rail and structural middle rolls; and finishing mills where housing design is too limited for iron rolls.
2.10-2.80	Finishing rolls to meet unusual conditions.

The above applications are not a rigid classification due to the wide variation of conditions from mill to mill. Adjustments in carbon and alloy content are generally made to suit individual conditions.

Materials and the Manufacture of Bolts, Screws, and Nuts*

Bolts and Bolt Steels—The bolts that are most frequently used together with the steels from which they are made are listed in Table I.

Table I
Bolts, Screws, Nuts and the Steels From Which They Are Made

Classification	Steels for Bolts, Screws and Nuts, (S.A.E. steels except where indicated)					
Aircraft Bolts.....	<u>2330</u>					
Cap Screws.....	<u>1010</u>	<u>1020</u>	<u>1035</u>	<u>A²</u>	<u>1112</u>	<u>X1020</u>
	<u>1120</u>	<u>T1335</u>	<u>Y1335</u>	<u>3135</u>		
Carriage Bolts.....	<u>1010</u>	<u>1020</u>	<u>A²</u>	<u>1120</u>	<u>1035</u>	
Connecting Rod Bolts.....	<u>3135</u>	<u>D⁴</u>				
Lag Screws.....	<u>1010</u>	<u>1020</u>	<u>1120</u>	<u>A²</u>		
Machine Bolts.....	<u>1010</u>	<u>X1015</u>	<u>1020</u>	<u>1120</u>	<u>1035</u>	<u>2330</u>
	<u>3135</u>	<u>A²</u>				
Machine Screws.....	<u>1010</u>					
Plow Bolts.....	<u>1010</u>	<u>1020</u>	<u>A²</u>	<u>1120</u>		
Rim & Hub Bolts..	<u>1010</u>	<u>1020</u>	<u>1035</u>			
Rivets	<u>1010</u>	<u>1020</u>				
Set Screws ¹	<u>1010</u>	<u>1112</u>	<u>1035</u>	<u>2330</u>	<u>3135</u>	
Shackle Bolts.....	<u>1010</u>	<u>1020</u>	<u>X1314</u>	<u>X1315</u>		
Step Bolts.....	<u>1010</u>					
Stove Bolts.....	<u>1010</u>					
Track Bolts.....	<u>1025</u>	<u>1040</u>				
Nuts	<u>1112</u>	<u>B³</u>	<u>C⁴</u>			

¹Set screws made from plain carbon steels are usually case hardened.

²C 0.14-0.20; Mn 0.60-0.90; P 0.045 max; S 0.05 max; Si 0.075-0.15.

³C 0.08-0.15; Mn 0.30-0.90; P 0.045 max; S 0.15 max.

⁴C 0.10-0.20; Mn 0.60-0.90; P 0.045 max; S 0.15 max.

⁵C in special 5 point range; Mn 0.70-0.90; P 0.04 max; S 0.04 max; Si 0.20-0.30; Mo 0.15-0.25.

The underlined steels are furnished by the manufacturer unless otherwise specified. Where two or more steels are underlined for the same product, the selection of the steel is optional. Where no steel has been underlined there is no accepted practice.

Steels Used in the Bolt Industry (S.A.E. Steels)

Steel 1010—Steel 1010 is used for some commercial bolts made by the cold heading process where strength is not the governing factor.

The minimum tensile strength is 50,000 psi.† The tensile strength of bolts made from this steel varies with the size of the material, the process of manufacture, and the heat treatment. This steel is commonly used where case hardened bolts are required.

Steel 1112—Steel 1112 is used for the same purposes and reasons as 1010, but the bolts made from this steel are made by the screw machine process. Products milled from cold drawn bars of this steel will have an approximate yield point of 70,000 and an ultimate of 80,000 psi. When normalized, the approximate tensile strength is 60,000 psi. When cold drawn, the yield point of this steel is relatively close to its tensile strength.

Open hearth steel of practically this analysis is used for nuts made by the cold punch process (Table I).

Steel 1020—This steel is generally used for cold headed bolts where a higher tensile strength is required than that of bolts made from steel 1010. Tensile strengths will be found to vary greatly between bolts of the upper and lower carbon limits of the analysis.

*This article was prepared by the Subcommittee on Bolts, Screws, and Nuts. The membership of the subcommittee was as follows: H. B. Pulsifer, chairman; C. L. Harvey, and C. E. Zwahl.

†The physical properties quoted in this practice are all based on machined tensile specimens.

The usual tensile strength of the heat treated bolt is 80,000 and the yield point 60,000 psi.

This steel is frequently used cold drawn for the manufacture of screw machine products. When cold drawn, it has a tensile strength of approximately 75,000 and a yield point of 60,000 psi.

A steel of practically this analysis, but with high sulphur, is used for the production of nuts made by the hot and cold punched processes (Table I). Where an open hearth steel is preferred to a Bessemer product, this steel replaces 1112.

Steel 1035—This steel is used for cold headed bolts where a higher tensile strength is required.

Bolts made from this steel are used for severe service conditions. After suitable heat treatment, the minimum tensile strength is 100,000 psi., combined with good ductility (minimum of 12% elongation in 2 in. and 45% reduction of area). The Brinell hardness range of 196-269 is found to be satisfactory for most classes of work. This is the lowest carbon steel satisfactorily double heat treated to close limits.

This steel is also used for screw machine products.

Steels 2330 and 3135—Products made from these steels are used to resist fatigue and shock and where a minimum of 125,000 lb. tensile strength after heat treatment is required.

After suitable heat treatment, the average physical properties obtained with these steels are as follows:

Yield point 110,000 psi.; tensile strength 140,000 psi.; elongation 16% in 2 in.; reduction of area 55%.

Brinell hardness ranges of 228-269, 241-286, and 269-321 are usually specified, depending upon requirements.

Special Materials—For special purposes, bolts are made from stainless, noncorrosive, and nonferrous metals.

Manufacturing Processes

Cold Heading—Cold heading is a process of upsetting by which the steel is made to flow into various shapes while it is cold.

The solid die type and the open die type are the two cold heading machines in which upsetting is accomplished. As a rule, the solid die type is used where the product is of short length and also with medium length products which require a high grade finish with close tolerance limits. The open die type is usually employed for long lengths of work which cannot be handled successfully in the solid die machine. Both types of machines are designed to operate with one or more heading strokes. The number of strokes required depends upon the shape of head and the amount of metal to be upset. Most types of machines are adapted for feeding wire up to $\frac{3}{4}$ in. diameter from the coils.

Cold upsetting is limited by the design of head, because only a certain amount of metal will flow into certain shapes. Shapes with corners and squares are hard to fill out.

All the steels listed in this article, except 1112, 1120, X1314, and X1315 are satisfactorily used for cold heading bolts.

Hot Heading—The operation of hot heading is similar to cold heading except that the steel is upset while it is hot.

Trimming—When the round or button shaped head has been upset in the cold heading operation, but some other shaped head, such as hexagon or square, is desired, it is secured by a trimming operation. This trimming operation consists of forcing the upset button head through a die of the required shape.

Burnishing—In order to obtain a smoother finish on the side of a head, the trimming operation is sometimes followed by a burnishing operation. This consists of forcing the head of the bolt through a die of the same shape as the trimming die, but of slightly smaller size.

Shaving and Pointing—If the top and bottom of the heads have not been properly shaped in the heading operation, they can be finished in a shaving operation which consists of cutting the top and bottom of the heads to desired form. This is particularly true of cap screw blanks.

Pointing or chamfering the end of the body of bolts or screws is accomplished by holding the blank in a suitable fixture and machining the end to the desired form. This operation prepares the blank for threading and gives the proper finish to the threaded end of the bolt as well as facilitating easy entrance into a tapped hole.

Threading—Cutting threads is accomplished by holding the bolt in a suitable fixture and presenting it to a die head which contains chasers. The chasers cut the threads on the bolt. When the desired length of thread is cut, the die head opens and releases the bolt.

Roll threading is accomplished by rotating the blank between flat or circular dies, upon the faces of which angular grooves have been cut which correspond to the proper form and lead of the thread to be rolled. These dies form the thread by displacing stock from below the pitch diameter of the thread and filling out the crest of the thread with the displaced metal.

Heat Treatment—For the heat treatment of screws, bolts and nuts made from carbon steels consult the article or the Composition and Heat Treatment of Carbon Steels in this Handbook.

Products made from 2330 steel are quenched in oil from 1475-1525°F., and products made from 3135 steel are quenched in oil from 1500-1550°F. and tempered according to the requirements of the finished bolts.

Composition, Heat Treatment, and Care of Sling and Crane Chain*

Scope—This article is intended to cover the heat treatment and care of open link mild steel chain (having a carbon content of not over 0.15%) and wrought iron crane or dredge chain. It does not cover stud link anchor chain, or chains over 2 in. in size which must in general be given special consideration. The portion of the article referring to periodic heat treatment refers only to mild steel and wrought iron chain, and not to cast steel, high carbon or alloy heat treated chain or low carbon steel or low carbon chain which has been carburized or cyanide hardened. It does not cover corrosion resistant steel or acid resisting bronze or Monel metal chain.

Introduction—The reliability of chain depends upon the quality of the welded links and the metal from which they are made. It is of paramount importance to ascertain if the chain is of ample size to sustain the safe working load. The quality of the metal should be carefully and thoroughly tested by the chain manufacturer, both for chemical and physical properties; a metallographic examination is also considered desirable.

Wrought iron for dredge chain usually has the following approximate chemical composition: Carbon under 0.05%; and manganese 0.06% max.

The average physical properties of wrought iron for chain are as follows: Tensile strength 46,000 psi.; yield point 23,000 psi.; elongation in 8 in. 26%; and reduction of area 40%.

Other tests that are often performed on wrought iron for chain are: Cold bend, quench bend, and drift tests. In addition, a cold feathering test may be applied by flaring the end of the bar under a hammer. This test is an aid in judging the workmanship put into the welded fagot. The results of these tests should show a high degree of ductility, and a fibrous, silky fracture free from bright spots.

Because mild steel requires different welding temperatures and methods than wrought iron, a satisfactory weld may not be obtained if the two materials are mixed in rerolling or reheating processes. To determine if an admixture of wrought iron and steel has been used, metallographic examination should be resorted to.

Low carbon steels are largely used for small chain other than sling chain, but in large sizes there are welding difficulties which are not encountered with wrought iron. Most chain above 1½ in., therefore, is made of wrought iron.

Normalizing, Testing, and Inspecting After Welding

Normalizing—After the welding operation has been properly performed, the welded or adjacent portion will not need a normalizing treatment to refine the structure, but in the case of large chain, such as ship anchor chains, portions of the link adjacent to the welds have been heated to or near the welding temperature, and if not hot worked, a weak, coarse, crystalline structure is developed which requires a normalizing treatment for refinement.

To normalize, the chain is placed in the annealing furnace, usually of the car bottom type, and heated until the complete charge, top, center, and bottom is at a temperature of 1750°F. The charge is held at this temperature for 10-15 min., or until the heat has completely penetrated the work. The car, if the car bottom type has been used, is then drawn out and the chain allowed to cool in the air. In other furnace types, the furnace doors may be opened or the chain removed from the furnace and allowed to cool on the shop floor.

Proof Test and Inspection—After cooling, the chain is proof tested. The test consists of fastening one end of the chain to the head of the testing machine and the other end to the anchor crosshead. The proof load for proof coil (steel) chain is usually 50% of the breaking load. For high grade wrought iron crane chain

*This article was prepared by the Subcommittee on the Heat Treatment and Care of Sling and Crane Chain. The membership of the subcommittee was as follows: A. V. deForest, Chairman; F. E. McKinney, C. G. Lutts and L. W. Hopkins. (Revised in 1938 by C. G. Lutts and L. W. Hopkins.)

the proof load is usually established at 33-38% of the breaking load. The justification for lower proof for wrought iron chain lies in the fact that it is often used in places where it is called upon to absorb high impact loads. It therefore should not be elongated in the proof test beyond that point necessary to detect defective welds or materials. Each link is then carefully inspected for flaws or other defects. Link measurements are made to determine if the chain has stretched beyond the specified dimensions. All chain suffers permanent elongation after the proof test.


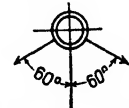


After subjecting the chain to a proof test, it may be annealed and the yield point thereby lowered. This step makes overloading more evident and to that extent increases the factor of safety. Because of the increased cost this operation is usually dispensed with, so the problem should be referred to the manufacturer before this particular annealing operation is specified.

Care and Use of Chain—Overloading is probably the most serious service abuse to which chain is subjected. A new chain may be impaired by overloading the first few times it is used. The elasticity of the chain metal is sufficient to take care of the safe working load. If the chain has not been overloaded, or stressed beyond the yield point, the chain will regain normal shape as soon as it is relieved of its load. When stressed beyond the yield point by an overload the metal does not go back to its normal condition or shape after the load is removed. When the yield point of the metal is once passed by an overload, the chain is never as strong under impact as before it had been stretched. If the chain is carefully measured at frequent intervals, any elongation that is not the result of wear is sure proof of overload.

Improper application of the chain sets up stresses that are far in excess of those caused by the weight of the load lifted, and which may be the cause of sudden failure. These increased stresses may be caused by any of the following:

1. Sudden application of the load, shocks, and sudden jolts.
2. Twisting of chain, kinks in chain, and crossing of chain.
3. Bending of links around sharp corners.
4. Excessive angles beyond that for which the sling is designed between the branches or legs of a double sling chain.

Table I
Safe Load in Pounds for Sling Chains Under Different Loading Conditions

Nominal Dia. of Chain Stock in in.	   			
	Single Leg Sling Capacity in lb.	Double Leg Sling Capacity in lb.	Double Leg Sling Capacity in lb.	Double Leg Sling Capacity in lb.
1/4	1,060	1,060	1,480	1,850
5/16	1,655	1,655	2,320	2,900
3/8	2,385	2,385	3,340	4,170
7/16	3,250	3,250	4,550	5,680
1/2	4,240	4,240	5,940	7,420
5/8	5,370	5,370	7,520	9,400
3/4	6,630	6,630	9,270	11,600
7/8	9,540	9,540	13,300	16,700
1	12,960	12,960	18,100	22,700
1 1/8	16,950	16,950	23,750	29,600
1 1/4	20,040	20,040	27,000	35,020
1 1/2	24,750	24,750	34,600	43,300
1 3/4	29,910	29,910	41,800	52,300
1 7/8	35,600	35,600	49,800	62,250
2	41,800	41,800	58,500	73,200
2 1/4	48,450	48,450	67,800	84,800
2 1/2	55,300	55,300	77,800	96,800
2 3/4	63,300	63,300	88,600	111,000

Failure Caused by Repeated Loading—Chain may break without showing elongation if loaded below the yield point a sufficient number of times. Failure may take place by ordinary fatigue, but is much more likely to occur by the following mechanism: Through the repeated peening action of the chain links against each other and their being dropped and hit against stone or metal, the surface of the soft iron is given a work hardened skin. Under impact loads, usually difficult to

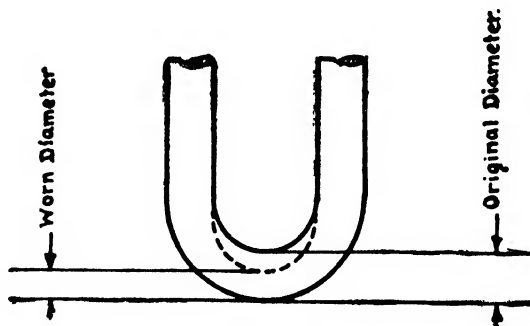
avoid, this skin is broken and the crack constitutes a notch which localizes stress and weakens the chain under conditions of further impact or repeated load. This hard skin may be removed and the impact strength of the chain maintained by periodic annealing. How often this is desirable depends on the particular service involved.

Angle of Sling Chains—The angle between the legs of the branches of a double sling chain should always be taken into consideration, especially when handling

Table II
Reduced Diameter of Link Stock in Chain Slings
Original Safety Factor = 7

Chain Size, in.	Reduced Safety Factors—			
	6	5	4	3
	Reduced Dia., in.			
¼	0.23	0.21	0.19	0.16
⅜	0.35	0.32	0.30	0.25
½	0.47	0.42	0.38	0.33
⅝	0.58	0.52	0.47	0.42
¾	0.70	0.63	0.57	0.49
⅞	0.81	0.74	0.66	0.57
1	0.93	0.84	0.75	0.66
1 ¼	1.04	0.95	0.85	0.73
1 ½	1.17	1.05	0.95	0.82
1 ¾	1.28	1.16	1.04	0.90
1 ½	1.39	1.26	1.13	0.98
1 ¾	1.50	1.37	1.22	1.06
1 ¾	1.63	1.47	1.32	1.15
1 ¾	1.73	1.58	1.42	1.23
2	1.86	1.68	1.51	1.31

Links to be measured at point of greatest wear.



Example:

A ½ in. chain is worn to about 0.40 in. in dia.
The remaining safety factor, full load, is (from table)
about 4.5.

heavy loads. As this angle increases, the angle between the legs and the work decreases. This reduces greatly the safe working load of the chain, because as the angle between the two legs of the chain increases the tension in each leg is also increased. The safe load in pounds for double sling chains, using different angles between the legs, is given in Table I.

Factor of Safety—Chain is always manufactured with a factor of safety sufficient to take care of a reasonable amount of abuse, but even this is of little avail with the careless handling which is given some chain.

The cold working caused from overloading will increase the breaking load, but decreases the ductility and resistance to shock, thereby reducing the factor of

safety. Chain links are reduced in diameter, due to dirt, grit, and abrasives grinding between the links when the load is applied. As the diameter is reduced, the factor of safety is lowered. In Table II is given the factor of safety for reduced chain links caused by wear.

If properly carried out, annealing will automatically increase the factor of safety, except where the link is reduced in diameter by wear. Annealing should not be done periodically as a "cure all," but carried out in conjunction with careful inspection. Inspection and measurements of the chain will give notice of any abuse. Wear, however, will cause elongation of the chain, so it is necessary to distinguish between this effect and the elongation caused from overload.

Annealing can restore ductility only in the metal of the reduced cross section and does not restore the chain to its original condition because the effects of the permanent deformation to the links are unchanged. No chain should be used on heavy work after it has been badly overloaded and has thereby become deformed. The tensile strength may not be impaired but the deformation of the original links considerably reduces the reserve of shock resistance in the links.

Chains that run over sheaves, such as hoist chains, should not be heat treated, except by the manufacturer, because these chains are very carefully proof loaded and gaged to sheave dimensions before being put into service.

COMPOSITION AND HEAT TREATMENT OF SLING AND CRANE CHAIN

General—This article covers the process to be followed for the annealing of sling and crane chain.

Process—The process of annealing chain consists of loading the furnace, heating, and cooling the chain.

Loading the Furnace—Place the chain in uniform layers on the furnace bottom so as to expose maximum surface area. To prevent scale from forming, a hood should be placed over the chain and the edges of the hood sealed with sand. The openings of the hood are sealed with fire clay.

Table III
Annealing Treatment for Iron and Steel Sling and Crane Chains

Dia. of Chain Link, In.	Iron Chain Annealing Temp., °F. ¹	Steel Chain Annealing Temp., °F. ¹	Time of Holding at Temp., hr.	Cool in
¼ to ½	1350-1375	1600-1650	¼	Air
¾ to 1½	1350-1375	1600-1650	¾	Air
1½ and above	1350-1375	1600-1650	2	Air

¹In case of doubt as to whether the chain to be treated is iron or steel, a temperature of 1350-1375°F. should be used. This practice will thoroughly relieve any strain or work hardening from iron chain without excessive scaling or softening of chain. This low temperature will theoretically produce some grain growth or recrystallization in steel chain, but it has been determined by experience that this has a negligible effect on the chain and is to be preferred to excessive scaling.

Heating—Heat to the temperatures given in Table III and hold at temperature for the time specified. The heat should thoroughly penetrate the work, and the top, center, and bottom of the charge should reach approximately the same temperature.

A sufficient number of thermocouples should be used to assure uniform temperature throughout the charge. A pyrometric record of the heating operation should be delivered with the annealed chain.

Cooling—After the chain has been held at the annealing temperature for sufficient time, the charge is pulled onto the cooling platform, or onto the floor. The chain should be spread in single layers, with ample space between each chain, so as to cool rapidly and uniformly to room temperature.

After annealing it is desirable that the chain be proof tested and reinspected for weld defects and defective links. The annealing treatment serves the purpose of burning off dirt and grease adhering to the chain, and thus facilitates inspection.

Precautions to Be Used with Chain

- Don't overload a chain.
- Don't apply a load to a chain suddenly.
- Don't fasten chain over sharp corners or edges.
- Don't cross a chain, twist it or put a kink in it.
- Don't take chances; if a chain does not look safe, or does not pass inspection, scrap it.
- Don't use a chain at small angles to the work.
- Don't force a chain or hook into a place by hammering.
- Don't carry a load on the point of the hook.
- Don't insert the point of the hook into a link.
- Don't let the load rest on the chain.
- Don't drag a chain from under the load.
- Don't roll over jobs with chain, use ropes.
- Don't think a chain is good because it is new; a new chain can be ruined by a single overload.
- Don't trust a chain with stretched or stiff links.
- Don't allow heavy weights to fall on chain.
- Don't allow chain to be exposed to extremely cold weather for any length of time.
- Don't apply sudden loads to extremely cold chain.
- Don't carry an unbalanced load.
- Don't, under any circumstances, use chains that are excessively pitted or corroded.
- Don't forget constant and careful inspection.

Reference

A.S.T.M. Specification A56-30 for Iron and Steel Chain, Book of Standards, 1930, pt. I, p. 459.

Wire Rope or Cable*

Introduction—Wire Rope is one of the most reliable structural materials available. It has the decided safety feature of indicating by surface inspection when it should be replaced. The wear and broken wires disclosed by such inspection, where corrosion is not present, will reasonably indicate the remaining strength. Slings made from wire rope, employing proper fittings, furnish the safest method for handling material.¹

There are six qualities of wire rope in commercial use as follows:

Grades	Approximate Carbon Content
Iron	0.05-0.15%
Traction steel.....	0.20-0.50%
Cast steel	0.30-0.60%
Extra strong cast or mild plow steel.....	0.55-0.70%
Plow steel	0.65-0.80%
Improved plow steel.....	0.70-0.85%

There are four standard constructions of wire rope; namely, 6x7, 6x19, 6x37, and 8x19. The figures mean that the rope is composed of 6 strands of 7 wires each, 6 strands of 19 wires, et cetera. There are, however, many variations in strand construction and the number of wires per strand may vary from 7-61 or even more should conditions require them.

To attain the different physical properties required in the various constructions, the individual wires of which a wire rope is composed are specially heat treated and cold drawn after the heat treatment, which produces the necessary toughness and strength. Any attempt, therefore, to eliminate the effect of service overstraining by annealing or any form of heat treatment, such as is given to chain, would obviously destroy the original properties of the wire obtained by the cold drawing. Such a heat treatment would ruin wire rope.

Qualities of Wire Rope

Iron Rope—Iron Rope is low in strength and soft as compared to steel rope, so consequently will stand little abrasion. It is pliable and tough, but its field is limited to uses where the abrasion is slight and the drums and sheaves are large. It is usually recommended for use on drum types of passenger elevators, for compensation and governor ropes, or for transmission of power by wire rope. It is not adapted to general hoisting or guy ropes. It is generally only furnished in the 6x7 and 6x19 standard construction.

Traction Steel Rope—This rope was developed particularly to meet the requirements of traction elevators on which it was necessary to have a high fatigue resistance, coupled with pliability and a softness so that the rope would not cut the sheaves. Traction steel rope therefore is not as strong as the Cast Steel Grade of rope.

Cast Steel Wire Rope—Although twice the strength of iron rope, cast steel wire rope is, comparatively speaking, a low strength steel hoisting rope and is only suitable for what is termed moderate duty. It is used on freight elevators where the operating tension is relatively low, as track cables on short span cableways, as hoist ropes on slow speed shallow mine installations that are equipped with large drums and sheaves, or as haulage rope under very favorable operating conditions. If the duty be heavy, the stronger and tougher grades of steel should be used.

Extra Strong Cast or Mild Plow Steel Rope—This rope is a stronger grade of cast steel and is substituted for cast steel rope where a slight increase in the factor of safety is desirable. In practically all cases the higher strength ropes prove more economical for general service.

Plow Steel Rope—Plow steel rope is made of high strength wire considerably stronger than either the cast steel or extra strong cast steel grades. This rope is well suited for the average hoisting conditions where loads are not excessive, where

*Prepared by Dr. H. C. Boynton and A. J. Morgan, John A. Roebling's Sons Co., Trenton, N. J., for the Subcommittee on Wire Rope and Cable. The membership of the subcommittee was as follows: B. B. Bachman, Chairman; H. C. Myra, H. Styri, and Dr. H. C. Boynton.

¹The terms "Cable" and "Wire Rope" are generally considered to be synonymous. However, when the term "Cable" is substituted for "Wire Rope", it is usually preceded by a descriptive adjective which places it in a more or less definite class; such as, a "Track Cable" on a cableway, or "Bridge Cable" as used in suspension bridges.

the sheaves are of normal diameter, and where the abrasion is not too severe. Plow Steel Rope has a general use such as on derricks, mine and coal hoists, cableways, cranes, conveyors and logging ropes.

Improved Plow Steel—This grade of rope is generally given a trade name by the manufacturers. It is a high strength rope recommended in place of the plow steel grade where the abrasion is severe or the rope is subjected to severe shocks, vibrations, or fatigue stresses. This rope is particularly adapted for severe mine duty, for logging lines, scraper dredge and rigging ropes, heavy cranes, ballast unloader ropes and excavating machinery.

Constructions of Wire Rope

Standard Coarse Laid Rope—The 6x7 wire rope construction is called "Standard Coarse Laid Rope". It is made of 6 strands of 7 wires each closed around a hemp center. It is much stiffer than standard hoisting rope and requires larger sheaves. This rope is used for heavy haulages with large equipment, wire rope transmissions, tramways, well drillings and sand lines.

Table I
Properties of Standard Steel Hoisting Rope (6x19)

Dia., in.	Approximate Strength in Tons of 2,000 lb.					
	Approximate Circumference, in.	Approx. Weight, lb. per ft.	Cast Steel	Extra Strong Cast or Mild Plow Steel	Plow Steel	Improved Plow Steel
3 1/4	8 3/4	12.10	212.0	234.0	256.0	294.0
2 1/2	7 1/4	10.00	176.0	195.0	214.0	246.0
2 1/4	7 1/4	8.10	144.0	160.0	176.0	202.0
2 1/4	6 3/4	7.23	128.0	143.0	157.0	181.0
2	6 1/4	6.40	114.0	127.0	140.0	161.0
1 3/4	5 1/4	5.63	100.0	112.0	123.0	142.0
1 3/4	5 1/4	4.90	88.0	98.0	108.0	124.0
1 3/4	5 1/4	4.23	76.0	85.0	94.0	108.0
1 3/4	4 3/4	3.60	65.0	72.5	80.5	92.5
1 3/4	4 3/4	3.03	55.0	61.5	68.0	78.5
1 3/4	3 3/4	2.50	46.0	51.0	56.5	65.0
1 3/4	3 3/4	2.03	37.0	41.5	46.0	53.0
1	3 1/4	1.60	29.5	33.0	36.5	42.0
3/4	2 3/4	1.23	22.8	25.4	28.0	32.2
3/4	2 3/4	0.90	16.8	18.7	20.6	23.7
3/4	2	0.63	11.8	13.1	14.4	16.6
1/2	1 3/4	0.51	9.6	10.6	11.7	13.5
1/2	1 3/4	0.40	7.7	8.5	9.4	10.8
1/2	1 3/4	0.31	6.0	6.6	7.3	8.4
1/2	1 1/4	0.23	4.5	5.0	5.5	6.3
1/2	1	0.16	3.2	3.5	3.9	4.5
1/4	3/4	0.10	2.1	2.3	2.5	2.9

Standard 6x19 Construction or Standard Hoisting Rope*—This rope is made of 6 strands, each of which is formed by twisting 19 wires together. The strands are finally closed around a hemp center. It is generally accepted that rope made with strands having not less than 16 and not more than 25 wires each belong to this general 6x19 class. This rope construction is more generally used for hoisting and other rope uses than all other constructions and is usually considered to be a flexible rope.

Table I gives the important sizes and properties for a Standard Hoisting rope of 6x19 construction made from Improved Plow Steel. The two constructions most generally furnished under the 6x19 Improved Plow Steel are the 6x19 Seale construction and the 6x19 Modified Seale or Filler wire construction, as illustrated in Figs. 1a and 1b.

6x37 Rope Construction—This rope consists of 6 strands, each of 37 wires. When each strand of the rope has not less than 29 or more than 46 wires composing it, the construction is generally considered in this class. This rope construction is generally termed as "Extra Flexible Hoisting Rope" and is usually recommended in place of "Standard Hoisting Rope" when the sheaves are found to be too small for the latter. The wires in this rope are necessarily much finer than those used in the standard hoisting rope with 19 wires to the strand and consequently are not as suitable to withstand severe abrasion.

*The 6x19 construction is probably used more often than the others, so much so that it is called "Standard".

8x19 Rope Construction—This construction is composed of 8 strands of 19 wires each closed around a hemp center. It is generally used where sheaves of small diameter must be employed and the abrasion is light. This rope construction is generally considered to be an "Extra Flexible Hoisting Rope" and sometimes may be considered to be interchangeable with 6x37 rope construction. The metallic area of the 8 strand rope is not so great as the 6 strand rope, but under severe bending conditions the decrease in strength is largely offset by the greater pliability.



Fig. 1a—Seale construction (6x19)



Fig. 1b—Modified Seale construction (6x19)

This rope distorts from its circular cross section more readily than a 6 strand rope so conditions of service which cause crushing require a 6 strand in preference to an 8 strand rope.

Proper Working Loads

—It is never advisable for the working load of wire

rope, particularly running ropes, to exceed one-fifth of the breaking strength. This means that the factor of safety should be not less than five. To determine proper working load, divide the breaking strength by the proper factor of safety. For example, a 1 in. diameter 6x19 Improved Plow Steel Rope has a breaking strength of 42 tons (Table I), and with a factor of safety of five, the proper working load would not be over 8.4 tons.

Factors of safety in excess of five, varying up to eight and even more, are often required for safe and economical operation. The proper factor of safety for a wire rope should be determined by careful and thorough consideration of all pertinent data. Such data should include all loads; acceleration; deceleration; rope speed; rope attachments; the number, size and arrangement of all sheaves and drums; existing conditions causing corrosion and abrasion; length of rope in service; economical rope life and the degree of danger to life and property.

Proper Sizes of Sheaves and Drums—To obtain most economical wire rope service, sheaves and drums should be carefully examined for proper size, free running, and proper groove diameters. It is advisable to design the sheave and drum equipment so that the tread diameters are approximately as follows:

Recommended Average Diameters for Sheaves and Drums

- For 6 x 7 Rope, 72 times rope diameter
- For 6 x 19 Rope, 45 times rope diameter
- For 6 x 37 Rope, 27 times rope diameter
- For 8 x 19 Rope, 31 times rope diameter

For economical service, various conditions allow, and often require, changes from these diameters. For example, on larger hoisting installations, sheaves for use with a 6x7 rope are sometimes set at 96 times the rope diameter and, for a 6x19 rope, sometimes as high as 90 times the rope diameter.

It is also true that for certain classes of service, ratios smaller than these are possible and economical, although larger diameters give increased life, but it is advisable never to allow the sheave and drum diameters to be set below the following:

Minimum Diameters for Sheaves and Drums

- For 6 x 7 Rope, 42 times rope diameter
- For 6 x 19 Rope, 30 times rope diameter
- For 6 x 37 Rope, 18 times rope diameter
- For 8 x 19 Rope, 21 times rope diameter

Rope and cable subjected to intense sheave or drum pressures or operating under conditions of severe heat are often manufactured with metallic centers instead of the usual hemp core. This center may be in the form of a strand or an independent wire rope. If such a center be used, the rope strength given in Table I may be increased by 7½% and the rope weight by 10%.

Storage—Particular care should be taken in storing wire rope to avoid damage. The rope should be stored in a dry place. It should not be allowed to become so hot as to injure the hemp center. To prevent destructive corrosive action on the steel, the storage place should be free from chemicals or gas from same.

Handling—Care should be taken in handling so that the rope is neither twisted nor untwisted. Kinks of any nature or the pulling down of loops to small diameters should be avoided. The wires are damaged beyond the elastic limit at such points and in subsequent service will break rapidly, producing a condition which is erroneously termed a bad spot in the wire rope. A spot like this is due to a kink placed in the rope either prior to or during its service.

Cutting—Before the actual cutting operation, proper servings* should always be placed on each side of the point where the rope is to be cut. Such a procedure is absolutely necessary in order to prevent the unlaying or the rotating of the strands. It is advisable to use a minimum of three servings on each side of the cut. The proper method for applying servings is shown in Fig. 2.

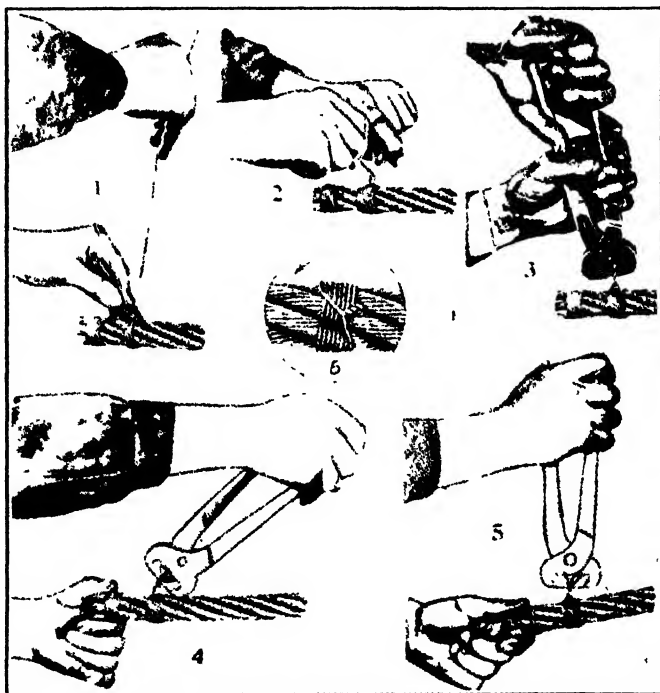


Fig. 2—Applying servings on a wire rope.

1. Wind the serving wire on the rope by hand, keeping the coils together and considerable tension on the wire. 2. Twist the ends of the wire together counterclockwise by hand so that the twisted portion of the wires is near the middle of the serving. 3. Using "Carew" cutters, tighten the twist just enough to take up the slack. Do not try to tighten the serving by twisting. 4. Tighten the serving by prying the twist away from the axis of the rope with the cutters. 5. Tighten the twist again as in (3). Repeat (4) and (5) as often as is necessary to make the serving tight. Cut off the ends of the wires and pound the twist flat against the rope. 6. The appearance of the finished serving.

Attachments—There are several ways in which the rope ends may be secured. The desirable one, and the one which develops 100% of the rope strength, is a socket connection. The proper method of attaching sockets is shown in Fig. 3.

In preparing the wire for socketing, the hemp center is entirely removed and the "brush" of separated wires is never dipped over three-quarters of its length in the acid so no trouble from corrosion occurs, moreover a slight film of hydrochloric acid acts as a flux to assist the amalgamation of the zinc to the "brush".

A thimble spliced in one end of the rope is often used for an attachment. Its efficiency varies from 75-90% of the rope strength, depending upon the rope size.

*Servings are sometimes called "seizings," and are soft wire fastenings secured around the rope to maintain its manufactured condition.

The thimble connection is also used with wire rope clips. This attachment has about the same efficiency as the splice. It is essential, however, in order that maximum efficiency be obtained that the clips be applied one rope lay apart, tightened securely and the U-bolts of the clips always placed on the dead end of the rope. The use of improperly designed clips or improper clip attachments results in strengths as low as 60% of the ultimate strength or less. The thimble is also used with 3-bolt clamps and this efficiency, when the clamps are properly designed, runs about the same or in excess of that obtained by use of clips. Clips and clamps should be tightened after about an hour's run and at the regular inspection intervals after that. It is essential in all of these connections employing the thimble that a proper design of wire rope thimble be used. It should be one which has a sufficient size of eye and also one which furnishes the proper support to the rope.

Lubrication—The subject of wire rope lubrication is one which should be given careful consideration. Light applications of a comparatively thin oil are usually sufficient for elevator ropes which are not exposed to the elements; while the conditions to be met in a mine shaft require a much heavier lubricant and a protector against the severe inroads of corrosion.

It is not possible for the manufacturers to place sufficient lubrication within a rope to last throughout its entire life. It is essential that a wire rope be lubricated internally as well as externally to reduce internal friction and protection against corrosion. When corrosion starts inside a wire rope its injurious effect can seldom be seen and cannot be arrested before the service and the safety of the wire rope are affected. The lubricant used should preferably be one recommended by the rope manufacturer.

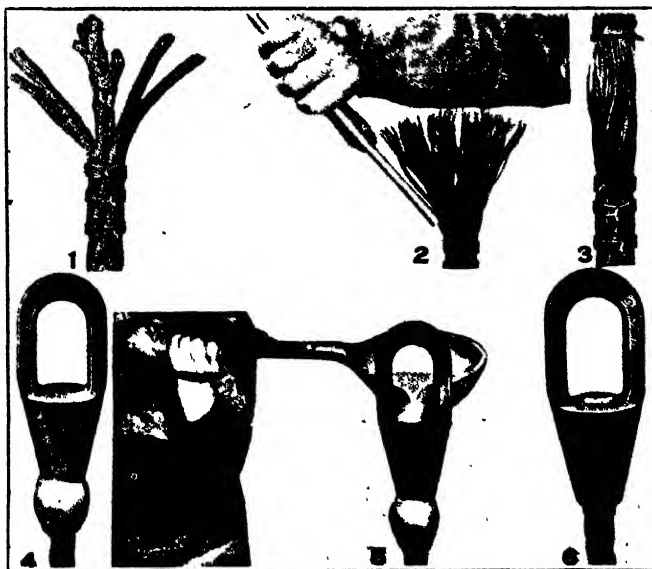


Fig. 3—Socketing wire rope.

1. Measure from end of rope a length equal to basket of socket. Serve at this point with not less than three wraps. Cut out hemp center—open strands. 2. Separate wires in strands, straighten by means of iron pipe, cleanse with kerosene oil, wipe dry. 3. Dip wires into one-half muriatic acid, one-half water (use no stronger solution). Keep wires in long enough to be thoroughly cleansed—wipe dry, serve end that socket may slip over all of wires. 4. After placing on socket, cut serving wire at top—have all wires evenly distributed and even with top of basket—place fire clay around bottom of socket. 5. Pour in molten pure zinc—do not use babbitt. 6. Remove all servings except one nearest socket. After cooling it is ready for service.

The correct lubricant should be one which when applied hot will penetrate thoroughly into the rope and on cooling congeal sufficiently so that it will not drip off, but rather form a plastic coating on the wire. The lubricant should

also be free from ingredients which would be injurious to the rope. Improper lubricants which harden on the surface will result in more damage than benefit, because they keep subsequent lubricants out and let in and keep in moisture. This condition accelerates corrosion.

In the American Engineering Standards Committee Paper, dated Feb. 24, 1927, is a set of rules for the selection of wire rope lubricants.

Sheave and Drum Grooves—Improper sheave or drum grooves undoubtedly result in more damage to wire rope than does any other single factor, so consequently cause irregular and uncertain rope service. It is essential that the grooves be of sufficient size for operating with new ropes when installed. The grooves are generally worn down by service; the degree of wear being dependent upon the radial pressure and the material of which the sheave is made. The grooves wear to the diameter of the worn rope operated over them and consequently become small for the new rope. This causes the new rope to receive extra abrasion and distortion which is very detrimental. Sheaves and drums should be inspected before the installation of the new rope and where the groove diameters have worn to limits in excess of those given below, the sheaves should be replaced or remachined so that the groove diameter will correspond to the following limits:

For ropes $\frac{1}{4}$ – $\frac{1}{2}$ in. dia., inclusive, groove dia. should be $\frac{1}{16}$ in. greater than rope dia.
 For ropes $\frac{3}{4}$ – $1\frac{1}{4}$ in. dia., inclusive, groove dia. should be $\frac{1}{8}$ in. greater than rope dia.
 For ropes $1\frac{1}{2}$ – $2\frac{1}{4}$ in. dia., inclusive, groove dia. should be $\frac{1}{4}$ in. greater than rope dia.
 For ropes $2\frac{1}{2}$ – $3\frac{1}{2}$ in. dia., inclusive, groove dia. should be $\frac{3}{8}$ in. greater than rope dia.

Removal of Ropes from Service—It is first necessary to determine the factor of safety to which a rope may safely deteriorate. The importance of this will be appreciated since ropes in some places would not endanger life or property should they break. Breakage in other places would be highly dangerous, so the minimum factor of safety must be set for such installations. In general, ropes which have the outside wires reduced 50% of their diameter by abrasion are likely to break rapidly. With some ropes many wires start breaking before this amount of abrasion is reached. It is, therefore, the number and the distribution of the broken wires together with the amount of abrasion which would indicate the remaining strength of the wire rope. The proper way to count a rope for broken wires is to count the number of such broken wires by strands per rope lay. By rope lay is meant that length of rope in which a strand makes one complete revolution about the rope axis. The worst rope lay counted should be the one on which to base the estimate of remaining strength or on which to base the decision as to whether or not the rope should be removed from service. The rapidity with which broken wires develop indicates the degree of fatigue and where the broken wires develop rapidly the rope should be carefully watched, since it will, undoubtedly, have to be removed soon thereafter.

An estimate of remaining strength or decision as to the safety of the rope cannot safely be made where corrosion is a factor, due to acid mine waters and corroding gases. When corrosion occurs in a wire rope it is impossible to estimate remaining strength or state that the rope is safe without an actual ultimate strength test of the rope. Should this test prove satisfactory there is no definite assurance that the balance of the rope is equally as good as the piece tested.

Long life for wire rope depends upon:

- Proper quality of wire used;
- Right construction for installation at hand;
- Large sheaves, with proper grooves;
- Correct lubricants, applied hot for internal and external lubrication;
- Prevention of corrosion;
- Careful supervision to prevent "kinking" or "looping" in installation, and overloading in service;
- Keeping count of broken wires, looking out for fatigue.

Wire rope is one of the most reliable of structural materials, but it should be realized that a wire rope is essentially a machine, in that it is composed of many parts functioning as a unit with the individual wires acting as bearing surfaces, and as such is subjected to pressure and wear. It will be readily apparent that the ultimate service will depend primarily upon its maintenance and care.

Nonferrous Section

A Record of Appreciation

This section of Metals Handbook was prepared by the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers through a co-operative arrangement with the American Society for Metals.

The Nonferrous Data Sheet Committee of the Institute of Metals Division, in charge of the preparation of the nonferrous articles, has again included much new material of a practical nature on the properties, technology, and applications of nonferrous metals and their alloys.

The members of the Committee, the authors and subcommittee members have given their whole-hearted co-operation in accumulating and presenting the data for this section of Metals Handbook. We wish to take this opportunity of extending our appreciation to all of the individuals mentioned above and to the American Institute of Mining and Metallurgical Engineers for this splendid assistance and the outstanding results it has produced. Their work has provided for the nonferrous industry a reference volume of distinct importance and helpfulness.


The personnel of the Nonferrous Data Sheet Committee for the 1939 edition of Metals Handbook was as follows:

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Nonferrous Section—General

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Hot Plastic Working of Nonferrous Metals

By Dr. C. H. Mathewson*

Hot working is usually defined as working above the recrystallization temperature, so as to insure recrystallization and recovery or retention of normal properties in spite of the plastic deformation.

A satisfactory scientific foundation for the generality of hot working operations requires the development of complete information in the following directions: (a) Stress-strain curves at temperatures throughout the potential hot working range and with a rate of application of stress comparable to that desired in the intended hot working operation. (b) From such curves an evaluation of the energy requirements for economical operation and of the toughness or ability of the metal to withstand the process. Thus, the temperature selected for hot working should prevent any great increase in yield point of the metal during working, that is, should yield a flat stress-strain curve and there should be adequate elongation before fracture. (c) The effect of prior structural condition of the alloy and in particular of natural impurities. (d) The requirement of special properties in the metal imposed by the special mechanical characteristics of any given process, such as drawing, extrusion, forging, rolling, swaging. Thus, in drawing, the metal must have strength to support the plastic alteration through the die, while in swaging the metal is itself supported during deformation and may be worked at its minimum both of plasticity and strength.

The literature of metal technology shows no systematic or satisfactory accumulation of data on these points or development of other criteria for judging the hot working quality of metal. The performance of a metal in such operations is usually estimated in a rough, provisional manner by reference to its softening temperature after cold work, with an increment allowed for the higher temperature necessary to permit virtually instantaneous softening in a rapid deformational process. Data on ordinary static tensile strength and ductility at elevated temperatures are now available¹⁰ for many of the ordinary commercial alloys, and are of certain value in indicating proper working temperatures. The details of performance are then settled purely by the method of trial and error. Similarly, the effect of impurities and the requirements of special processes must be established by a suitable empirical testing procedure. There is a general tendency to credit a high value of reduction of area in the hot tension test, accompanied by moderate tensile strength, as especially indicative of useful plasticity. For example, in the tests reported by Price⁵ copper has a percentage reduction of area exceeding 90 in the temperature range 930 to 1830°F., with tensile strength falling gradually from about 9,000 to about 1,200 psi. In the table at the end of this article, 1550° is given as an optimum hot rolling temperature for copper to maintain softness, but the metal may be satisfactorily hot rolled at all temperatures indicated above, though with some difficulty at the highest temperatures on account of its extremely low strength in this region.

Certain established practices have arisen, perhaps with little attention from the scientific point of view, and rather definite statements may be made, as in the article on Hot and Cold Working of Copper Alloys in this Handbook concerning the adaptability of industrial alloys to the various hot working operations of extrusion, stamping, pressing, rolling, and piercing. Much information of this character may be found in the various articles on metal technology in this Handbook.

For rapid deformations as in stamping or forging the requirements of (a) may be realized in a drop hammer test in which the decrease in height of a cylindrical sample is plotted against the energy of the blow. Commonly, various approximations are accepted, such as compression for a given blow plotted against temperature, or composition,^{8, 9} from which suitable temperatures, or compositions, may be selected when attention is also directed to the manner in which the specimen stood the plastic alteration (absence of edge-cracking).

When the constitution of an alloy changes with temperature, impact tests on notched bars may show with particular clarity the existence of favorable and unfavorable temperature ranges of toughness. Thus the width of the brittle range in brass in the vicinity of 900°F. and its change with composition, as well as the effects of lead and tin are brought into prominence by the Izod test.^{11, 12}

However, there are good indications of this weakness in the ordinary tension test for elongation or reduction of area⁴ and the writer is not aware that any test

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revealing hot shortness, or far reaching plasticity and toughness, can be used as more than a general guide to direct experimentation with the particular equipment in which the given alloy must be deformed.

The empiricism necessary in this work is well stated by Morris:¹⁰

"For instance we wish to extrude a metal M. We know that we can extrude another metal Q at temperature T. We make a drop hammer test of metals M and Q and find that in order to obtain the same reduction in height as we find in metal Q at temperature T, we must heat metal M to temperature T'. T' is therefore the temperature at which we first try to extrude the metal M, with fair assurance that we shall be able at least to force the metal through the die. Much the same kind of reasoning can be applied to hot rolling. The tendency to crack in extrusion and rolling, however, must be ascertained largely through experience."

Concerning the effect of impurities, embrittlement due to segregation of a weak constituent in grain boundaries (that is, lead in alpha brass) and the great rise in resistance to deformation generally produced by solid solution even of small amounts of alloying elements (principally responsible for the contrast in properties between commercial and extremely pure metals) have been studied more in relation to cold

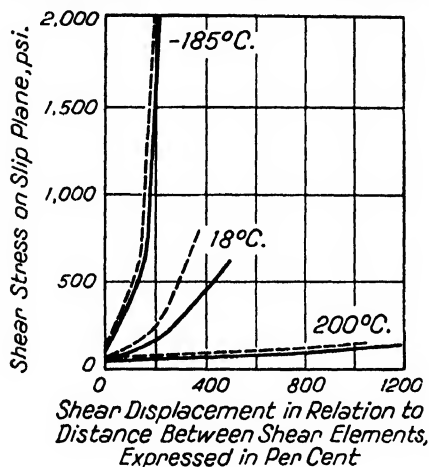


Fig. 1—Shear strengthening of single crystals of cadmium, according to Schmid and Boas.¹²

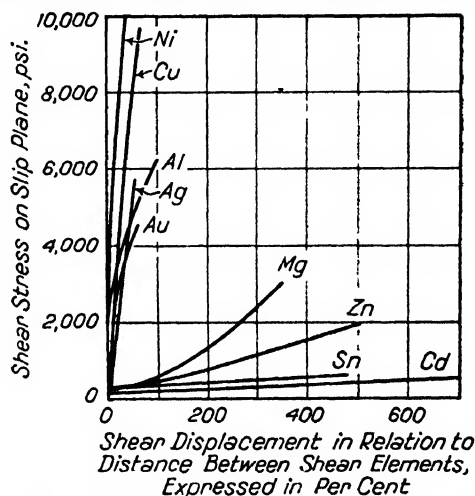


Fig. 2—Shear strengthening curves of metal crystals, according to Schmid and Boas.¹⁴

working than hot working but have brought certain well recognized limitations into commercial practice. For example, lead above a few thousandths of a per cent prevents the commercial hot working of alpha brass, but with Muntz metal, due probably to a more favorable distribution attending the structural adjustment of alpha and beta with temperature in the hot working range,⁹ lead in considerable quantity does not prevent the majority of hot working processes. Similarly, tin bronzes which contain the ($\alpha + \delta$) eutectoid show marked brittleness in the Izod test and cannot be successfully hot worked, while tin in solid solution yields good hot working bronzes.¹¹

Annealing or recrystallization temperatures as ordinarily determined do not properly define the softening points of metal while in a process of rapid deformation. The effect of temperature and rate of loading on hardening is particularly marked in this region of temperature as may be seen from Fig. 1. The solid curves show strengthening in single crystals of cadmium under a load applied at the rate of 140 psi. per minute and the dotted curves, strengthening under a load applied at a rate 100 times greater. It thus appears that in a region of low temperature where there is virtually no spontaneous recovery towards initial properties and in a region of high temperature where the recovery is substantially complete during the test, changing the temperature or the rate of loading has little effect on the strain hardening. In an intermediate region of temperature, which undoubtedly corresponds to the temperature at which ordinary softening and recrystallization begin in severely strain hardened polycrystalline material, much or little recovery may occur depending upon the rate of loading; and the final strain hardening of the metal varies according to these conditions. In the present case, the crystal after a shear of 400% at the

higher rate has a resistance to further shear of about 850 psi. and after the same amount of shear at the slower rate, a resistance of about $\frac{1}{2}$ this value.

Resolved stress, shearing deformation curves for room temperature loading have been obtained for the majority of common metals as shown in Fig. 2. As the slope of such curves is governed by the amount of recovery during the test, it appears that the tendency of the metals to recover from the strain hardening influence during deformation at ordinary temperature decreases in the order: (1) Cadmium, Tin (2) Zinc (3) Magnesium (4) Gold, Aluminum, Silver (5) Copper (6) Nickel. Recovery in these single crystals does not signify recrystallization, which, however, may be expected to accompany the recovery process at high (hot working) temperatures when, with increasing deformation, crumpling or nonuniform distortion of the crystal becomes too severe to permit a reversion to the unstrained condition without complete reorganization of the grain structure. This condition is rapidly attained in polycrystalline material, which recrystallizes even after a small amount of deformation. Such inequalities of deformation exert only a secondary influence on the amount of strain hardening and at a temperature of full recovery the occurrence of recrystallization does not appear to add materially to the softness attainable in the simple recovery process. From the above point of view, it is evident that the metals of Fig. 2 exhibit a decreasing tendency to soften or recrystallize after cold work in the order stated; that cadmium and tin would recrystallize at ordinary temperature, zinc and magnesium at not greatly elevated temperatures, and the others at successively higher temperatures. The effective temperature of hot working would also increase in this order but in a commercial operation would have to be determined by trial.

The following table gives temperatures of recrystallization after severe cold deformation, and favorable hot rolling temperatures of the ordinary commercially pure nonferrous metals.

Metal	Effective Softening Temp., °F. After Severe Cold Deformation (Approx. Complete Softening After 1 hr.)	Best Approx. Hot Rolling Temperature, °F. (For Softness) ^a
Lead	Approx. room temp.	Somewhat above room temp.
Tin	Approx. room temp.	Somewhat above room temp.
Zinc	200 ¹⁵	350
Magnesium	Between 200 and 400 ²	650 ¹⁶
Aluminum	525 ¹⁷	950 ¹⁸
Copper	700 ¹⁹	1550 ¹⁹
Nickel	1400 (max.) ²¹	2200 ²⁰

^aThis means in general the highest temperature for satisfactory operation. Special requirements of mechanical properties are met by rolling at lower temperatures.

¹A good bibliography of this general subject will be found in the footnote references to the section on "Hot Forming," p. 91 of *Praktische Metallkunde*, pt. II, by G. Sachs, Springer, Berlin, 1934.

²R. L. Templin and D. A. Paul, The Mechanical Properties of Aluminum and Magnesium Alloys at Elevated Temperatures, A.S.T.M. Symposium on Effect of Temperature on Metals, 1931, p. 290.

³H. A. Anderson, Zinc Alloys for High and Low Temperature Service, p. 271.

⁴E. R. Darby, Properties of Bearing Metals at Normal and Elevated Temperatures, p. 316.

⁵W. B. Price, Properties of Copper and Some of its Important Industrial Alloys at Elevated Temperatures, p. 340.

⁶N. B. Pilling and R. Worthington, Effect of Temperature on Some Properties of Iron-Chromium-Nickel Alloys, p. 495.

⁷C. A. Crawford and R. Worthington, Nickel and Nickel Alloys, p. 557.

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Soldering (Soft Solders)*

Scope—The use and application of alloys such as lead-tin, lead-tin-cadmium, and others are discussed in this article. Attention is given to varieties of metals which can be soldered, types of fluxes and methods of application.

Definition—The alloys mentioned are generally referred to as soft solders, thus distinguishing them from hard solders (brazing solders and silver solders), which are described on page 1210. The term soft solders in this discussion is restricted to alloys that are fusible at temperatures below 700°F., whereas the hard solders are fusible at or above 1300°F. Unfortunately there appear to be no satisfactory solders, with high ductility and strength, that melt between 700 and 1300°F. One of the distinctions between a soldered joint and a welded joint is that in the former, the metals to be joined are not heated to their melting points. Consequently one of the requisites for a solder is that its melting point must be lower than that of the metals being joined.

Materials Soldered—Solders are employed for joining cast or fabricated metals of various compositions. Principally these are: Iron, copper, nickel, lead, tin, zinc, and many of their alloys. Materials such as glass and porcelain may be joined by soldering after their surfaces have been coated with metal or metallized by metal spraying or other suitable processes.

A.S.T.M. Standard Solders—The following compositions of lead-tin alloys have been designated as standard in A.S.T.M. Standard Specifications for Solder Metal, B 32-21 (A.S.T.M. Standards, 1933, pt. I, Metals, p. 817):

Grade No	Tin, %	Lead Approx., %	Antimony Max., %	Copper Max., %	Zinc and Aluminum, %	Other Impurities Max., %
Class A						
0	63.00	37.00	0.12	0.08	None	0.10
1	50.00	50.00	0.12	0.08	None	0.10
2	45.00	55.00	0.12	0.08	None	0.10
3	40.00	60.00	0.12	0.08	None	0.10
4	37.50	62.50	0.12	0.08	None	0.10
5	33.00	67.00	0.12	0.08	None	0.10
Class B						
1	49.25	50.00	0.75	0.15	None	0.10
2	43.50	55.00	1.50	0.15	None	0.10
3	38.00	60.00	2.00	0.15	None	0.10
4	35.50	62.50	2.00	0.15	None	0.10
5	31.00	67.00	2.00	0.15	None	0.10

The permissible variation plus or minus in the percentage of tin shall not be over 1% of the tin contents specified in Section 4.

The above compositions have been approved as standard by the American Standards Association. The S.A.E. Specifications No. 1, 2 and 3 practically conform to these standards. Other soldering alloys are given in Table I.

Sweating Solders—Sweating solders usually vary between 37.5:62.5 and 50:50 tin-lead. The popular composition is 40:60 and 45:55. This is a trade designation which means the per cent tin by weight is placed first and the lead second.

Fundamentals—While it may not be essential for a solder to alloy with the metal surfaces where applied, it appears desirable for it to do so. For good soldering work these rules must be followed:

- (1) The metal surfaces to be soldered must be clean and free from foreign matter and objectionable grease.
- (2) The metal surfaces while soldering must attain a temperature above the solidus point of the solder.
- (3) The flux should be molten at temperatures below the solidus point of the solder so that it can avoid being entrapped in the solder in the joint.
- (4) All traces of corrosive fluxes should be removed with particular care after the joints have been made.

Preparation—Generally, the first step in tinning or soldering is a cleaning of the metals to be coated or joined. The operation may be mechanical as by scraping,

*This article was prepared by a subcommittee, the membership of which was: G. O. Hiers, Acting Chairman; W. A. Cowan, E. E. Schumacher, and W. H. Swanger.

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filing, or rubbing with sand or emery paper. Usually the preliminary cleaning is accomplished by chemical action with pickling solutions of acid or alkali. Frequently, metal parts to be joined by soldering are made from tinned sheet or wire in order to facilitate soldering. It is often desirable to apply a coating of pure tin or solder metal to the surfaces of metal parts to be joined subsequently by soldering.

For practical purposes, it is generally necessary to use a flux when soft soldering. The chief functions of fluxes are to prevent oxidation of the surfaces or to dissolve such oxides that may be present on these surfaces while they are being heated to the soldering temperature. They should also be fluid at the temperature of molten solder and be so applied that by gravity, capillarity or other forces the solder can displace the flux at the joint made. Mild fluxes such as tallow, stearin, and rosin particularly prevent oxidation but are not effective in removing oxides already present. Zinc chloride, with or without the addition of ammonium chloride, acts both as an oxidation preventive and a scavenger. Zinc chloride has a melting point of 689°F. and its eutectic mixture with ammonium chloride (71% ZnCl_2 , 29% NH_4Cl) has a melting point of 354°F., fortunately just below the melting point

Table I
Additional Alloys for Soldering and Other Uses

Tin	Per cent Anti-mony		Cadmium	Melting Range in °F.		Uses and Comments
	Lead			Liquidus	Solidus	
5	95			595	555	For coating and joining metals. For "high" temperatures.
10-20	90-80			580-545	500-361	For coating and joining metals. For "high" temperatures.
15-35	85-65			565-490	361	Low grade solder. For filling dents in automobile bodies.
37.5	60	2.5		435	367	Wiping solder for joining lead pipes and cable sheaths.
38-40	62-60			462-460	361	Wiping solder for joining lead pipes and cable sheaths. For automobile radiator cores and heating units.
45	55			437	361	For automobile radiator cores and roofing seams.
50	50			421	361	For general purposes. Most popular of all.
60	40			376	361	"Fine solder." For general purposes but particularly where the temperature requirements are critical.
95		5		464	450	For electrical work and copper tubing joints.
23	68		9	455	294	Wiping solder.
50	32		18	293	293	For fusibility, safety devices, and mounting micro specimens.
19	31		(50 Bi)	201	201	For fusibility, safety devices, mounting micro specimens, and fire prevention devices.
13	27		10 (50 Bi)	158	158	For fusibility, safety devices, and mounting micro specimens.
			95 (5 Ag)	734	639	For "high" temperatures.
			50 (50 Zn)	619	508	" "
			82.5 (17.5 Zn)	508	508	" "

The above solders and their uses are mentioned as typical. The classifications are informative and not complete or restrictive.

of the eutectic alloy, 62% tin, 38% lead. Therefore the zinc chloride-ammonium chloride eutectic mixture is desirable for use with the lead-tin eutectic solder (62% tin, 38% lead) when the latter is to be applied at a temperature just above its melting point. The ordinary flux solution is zinc chloride made by dissolving zinc in muriatic (hydrochloric) acid. A popular paste flux contains about 75% petroleum jelly, 20% zinc chloride, and 5% ammonium chloride with a small amount of water as an emulsifying agent. It is manufactured and sold by several companies.

Methods of Application—Most common metals and their alloys can be readily joined with solder. The method of application of solder to the metals to be joined varies according to the character of the metals, their position, the size of the parts to be joined, the speed with which the operation must be completed, and the shape, tensile strength and appearance required by the finished work. In every case, the

surfaces to be soldered must be brought to the melting temperature of the solder. The necessary heat is secured:

1. By repeatedly pouring the molten solder over the surfaces to be joined as in the wiping method; 2. By the use of the soldering iron or soldering copper; 3. By the use of blowtorch or electric arc; 4. By solder bath; 5. By sweating; 6. By spraying; and 7. By fusion of applied paste composed of atomized solder mixed with flux.

1. Wiping Methods—For joining sections of lead pipe, or of lead pipe with brass, bronze, or copper fittings with solder, or the joining of lead covered electrical cables using a lead sleeve, the wiping method is used. This method requires a high degree of skill and practice. The solder in a semiliquid state is poured slowly, and carefully distributed over and beyond the top and sides of the joint, which is being prepared, in order to furnish adequate heat for producing a good joint. Being in a fairly fluid condition, some of the solder drops off the joint onto the cloth which the workman holds under the joint. This dropped solder is pressed up against the bottom of the joint and the whole mass of hot solder is manipulated until every part of the joint is raised to a proper or "sweating" temperature, which insures a perfectly tight contact all-around. When this heat is attained, the pasty solder is shaped and rounded with the wiping pad, and all excess solder is wiped off as the joint slowly cools and the solder hardens.

Where the location prevents the use of a tool or mechanical device for joining lead pipes when soldering, the wiping method is used. The same method is employed in soldering joints to telephone cable sheathing for uniting a covering or sleeve which encloses connections of conductor wires. These joints must be capable of convenient reopening.

When joints are large, of a convenient shape, and are made by pouring from ladles, excellent adherence and soundness can be obtained by repeated pouring until sufficient heat is applied to properly form the joint. The excess solder in semi-solid form is wiped off upon subsequent cooling.

In wiping joints stearin in stick form is sometimes used for fluxing. Plumbers get some flux (tallow or lard oil) from the wiping cloth.

The wiping solders used in this country for making joints in pipes or for cable sheathing contain predominately 58-63% lead, the balance tin, although some users prefer the addition of up to 2% antimony (in filling joints in automobile bodies, an alloy is used somewhat as a wiping solder and usually contains about 30% tin and 70% lead). These alloys have an extended solidification range of about 140°F. and contain a considerable quantity of eutectic. The combination of these two factors makes possible the wiping of joints.¹ The use of cadmium substituted for some tin in the alloy has been thoroughly discussed in an article by Schumacher and Basch.²

2. Use of a Soldering Tool—A soldering tool is sometimes referred to as a soldering copper and sometimes as a soldering iron. It is usually copper, even when called an "iron". Before it can be used efficiently the iron must be "tinned" or coated with solder and maintained in a clean condition.

The tool is used in soldering sheet metals together where the sheets are either lapped or locked together and present a surface over which the soldering tool may be drawn.

The tool is heated to a temperature sufficient to quickly melt the solder, and is drawn along the edges to be joined at such a rate that the momentary high temperature of the edges together with the quickly molten state of the solder allows the formation of a tight waterproof seal. The soldering iron is also used in other work where there is a fire hazard and the use of a flame or molten solder poured over the surfaces is prohibitive.

Galvanized iron sheets and copper sheets used for roofing are generally soldered by means of the iron. Terne plate and tin plate are often similarly soldered.

3. Use of a Blowtorch—Where the metals to be joined or soldered are not large enough in diameter or rigid enough to permit the use of the wiping method or are not flat surfaces in position for the use of soldering copper, soldering is accomplished by playing the flames of a gasoline, kerosene, or alcohol blowtorch directly on the surfaces and then applying the solder cold in bar or wire form of appropriately small cross section. The heated surfaces melt the solder, excess solder being removed by wiping off before complete solidification. This method is in common usage by electrical workers in soldering wire joints and sweating on lugs.

4. *The Solder Bath*—Where the parts to be soldered are too numerous or too small for the use of the methods previously described the soldering is done by means of a molten bath.

The soldering of automobile radiators is a good illustration of this procedure. The radiator parts (cores) assembled into frames and therein tightly clamped have their ends dipped into a solder bath which is just deep enough to give the required depth to the joint. For making up the bath the solder may be purchased in the form of slabs weighing from 15-35 lb. Popular compositions for the bath are 50:50 and 40:60 tin-lead respectively, although more, and also less, tin-rich alloys are used by some manufacturers.

The soldering of tin cans is another good example. The cans are carried through the bath by a chain belt over a track which causes the cans to revolve. The track holds the cans at an angle of 45° so that the solder in the bath touches about ¼ in. of the bottom and side of the can thus making the joint. In a modern machine 300 cans per minute may be soldered in a single stream or procession.

5. *Soldering by Sweating*—The sweating process has been found best where a large number of metal objects are to be soldered with great rapidity and when they are of uniform size allowing the use of automatic machinery. Round tin cans, in addition to bath soldering, are also often sweat soldered and provide a good example of the method. The cans, mechanically assembled by forming and then crimping on heads and bottoms are carried on a moving chain belt over tracks which causes them to revolve while passing under a series of gas jets. The heated cans then pass under tubes which feed the correct amount of wire solder per can to the proper locations on the cans. The solder immediately melts on the heated cans and flows or sweats into the crimped joints, making securely soldered and air tight seams.

Other Methods—In soldering many specialties the usual soldering methods are often modified or combined and special tools devised to fit special conditions. However, no new principles are involved in any of these special shop practices.

Working Heat and Fluxing—A pot of solder should never be raised much beyond the necessary working temperature. On big work, where much heat is required to bring the metals to the proper temperature for efficient soldering, it is better practice to use a large pot carrying a large charge of solder at about the usual soldering temperature rather than to use a small pot and raise the temperature of the solder unusually high.

As the temperature of the molten solder is raised, the metal exposed to the action of oxygen in the air is oxidized unless protected by a hard soldering flux such as powdered borax, charcoal, and soda. When the molten solder is overheated in the air more tin than lead is lost proportionately because of somewhat preferential oxidation. If it is necessary to heat the solder excessively for any reason (as when a pot of solder has to be carried a relatively long distance), the metal should be covered with a hard soldering flux, as before mentioned. Stirring and skimming a pot of overheated solder are not recommended because of excessive loss by oxidation.

Upon solidification of a considerable quantity of 50:50 or similar solder, the primary crystals of lead sink to the bottom of the melting pot due to their greater density and permit the lead-tin eutectic to segregate toward the surface. To insure uniformity of composition of the solder, the alloy must be thoroughly stirred after melting and the temperature maintained above the complete liquefaction point (liquidus temperature) of the alloy.

In the consideration of fluxes attention should be directed to the kind of metals to be joined and their massiveness. Ordinarily it takes more heat to solder iron or steel than is required for soldering lead. Whenever a soldering iron is used, the heating is localized and the heat may be conducted away rapidly, consequently the iron must be exceptionally hot when the article is not preheated. In such cases, the use of rosin as a flux would be unsatisfactory since this material carbonizes at the higher temperatures thereby preventing rather than aiding soldering. When soldering large pieces of metal together, it is nearly always desirable to pre-tin parts individually before assemblage for soldering. This facilitates the soldering and makes stronger joints. Preheating is sometimes desirable. Before soldering cast iron the use of a cold pickling bath of 5% hydrofluoric acid is recommended.^a

Pastes or powders composed of pulverized tin or solder mixed with flux are on

the market and used to some extent. Tubular solder wire with a core consisting of rosin or other flux is quite popular. Adequate amounts of solder should be used in joints but economy demands no more than enough. To attain this end more expensive solders containing more tin are sometimes used because they flow better and less is required. To aid the consumer in the economical use of solder, soldering materials in suitable forms and of suitable dimensions are marketed by manufacturers. Some of the forms obtainable are tinner's bar, triangular bar, meter bar, ingot, wire in spools or in segments, drops, capping bar, slabs, powder, and tape, or ribbon.

The time required in making a good soldered joint may be extremely short. While prolonging of the period of time in which the solder is molten in a joint may increase the amount of alloying, the effect is generally not considered beneficial. When soldering copper, it is advisable to use a temperature below 752°F. in order to prevent the formation of the brittle copper-tin compound Cu_3Sn which, when present, tends to reduce the strength of a joint.

Mechanical Properties—Nightingale's tests¹ show 0.003 in. for a desirable thickness of a solder film on copper and 0.005 in. on steel. Crow⁴ previously indicated that the thinner the solder film the stronger the joint.

The Bureau of Standards⁵ investigated seams for copper roofing. It was decided that lap seams should be at least $\frac{3}{4}$ in. wide. For such a seam the maximum safe load was placed at approximately 350 lb. per in.² of seam area. The corresponding load for $\frac{1}{2}$ in. pre-tinned flat lock seams was 375 lb. per in.² of seam area. A 50:50 solder was used for the tests.

For automobile radiator cores of the honeycomb type 40% tin, 60% lead solders have been favored because of their supposedly greater vibration-fatigue resistance. Data for endurance limits are not available.

Tests have shown that tin-lead alloys containing only 3-8% tin have better strength at 302°F. than the richer tin alloys.

A 5:95 tin-lead alloy has found some popularity for use in joints maintained at elevated temperatures.

Owing to the fact that solder is frequently used to join metals stronger than itself it is often good policy to reinforce seams by crimping, interlocking, riveting, or bolting before soldering.⁶ Thus a joint can be made stronger by relieving the solder of the load, and making the major function of the solder that of hermetically sealing the seam.

Miscellaneous Notes—Aluminum may be soldered with lead-tin alloys or better with tin-rich alloys that contain considerable zinc. One method is to rub the aluminum surface beneath molten solder thereby piercing the oxide film and permitting alloying of the solder with the aluminum^{8, 10}. Brazing or welding is often preferred to soldering of aluminum.

When soldering stainless steel, ample time should be allowed for the flux to act properly before applying the solder.

For soldering zinc or galvanized iron, the presence of antimony in the solder is undesirable, because antimony forms an infusible compound with zinc, thereby spoiling the flow of the solder.

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Brazing and Related Joining Methods*

Introduction—Brazing is a term that is usually applied to a process for joining metals with alloys of copper and zinc which melt at temperatures appreciably below the melting points of the metals to be joined. The common brazing or spelter solders are composed of approximately equal parts of copper and zinc and melt at temperatures from 1600-1650°F., depending upon the relative proportion of the two metals. Many of the fundamental principles involved in the use of these alloys are similar to those governing the use of silver solders which have a lower range of melting points and bronze welding rods which have a higher range. The scope of this article has, therefore, been extended to include alloys having melting points ranging from approximately 1200-2250°F.

Preparation of the Joint—Clean and properly fitted joints are prerequisite to satisfactory bonding. All surface scale or oxides should be removed either by chemical or mechanical means. Oil, grease, and dirt of any description interfere with good work.

The allowable clearance between the surfaces to be joined will vary according to the alloy used, type of joint, method of heating and the metals joined. With free flowing brazing alloys such as silver solders, closely fitted joints with maximum clearance of a few thousandths of an inch will give the best results. When bronze welding rods are used it is common practice to make a "V" joint and fill the joint with successive layers of the brazing alloy.

Fluxes—The temperatures required for brazing cause a rapid oxidation of the surfaces of the joint if exposed to the air during the heating. A thin film of oxide will prevent proper bonding and the surfaces should be protected with a salt or combination of salts that will help to prevent oxidation and dissolve or flux any oxides that may form.

Common borax is a thin fluid at 1400°F. and at this temperature unites quickly with the oxides of most metals.

It contains approximately 47% water of crystallization, which is driven off when heated, thus causing the flux to "bubble". Fused borax is, therefore, preferred by some workmen and if used as a paste, it should be mixed with alcohol because the fused borax quickly takes up the water and becomes common crystalline borax again.

Boric acid is sometimes used alone as a flux but generally in combination with borax or other salts. It is not as active as borax for dissolving oxides of metals but has the property of spreading over the surface at a relatively low temperature and thus protects the surface from oxidizing. Combinations of borax and boric acid are extensively used, particularly with brazing alloys at temperatures above 1500°F.

The alkali bifluorides in combination with borax and boric acid are used as fluxes when joining metals having refractory oxides such as chromium in stainless steels. The potassium salts are more effective than the sodium and by varying the proportions of the salts enumerated in this and preceding paragraphs a wide range of fluxes can be produced to meet the different conditions encountered in brazing work.

There are many satisfactorily prepared fluxes available, some of which may contain phosphates or halogen salts, but regardless of the particular composition selected it is most important that it be applied in such a manner as to insure that all oxide films will be removed. Moreover, the flux should be a thin liquid at the brazing temperature in order to prevent inclusions which will subsequently give trouble. Both the surfaces of the joint and the brazing alloy should be protected with flux if the best results are to be obtained.

The flux may be used dry, in paste form, or by means of hot saturated solutions. When used in paste or hot solutions, it is advisable to brush the flux over the surfaces because a more uniform coating can be obtained and there is less chance for bare spots that will oxidize during the heating. When the brazing alloys are in granular form it is common practice to mix the flux with the alloy before spreading along the joint. Strip, wire, and rods can be coated before using or by dipping the end into a small can of flux paste just before applying to the joint, or by heating the rods and sprinkling the dry flux on them.

*This article was prepared by a subcommittee the membership of which was as follows: R. H. Leach, Chairman; J. R. Freeman, Jr., and Samuel Epstein.

Methods of Heating—The four principal methods of supplying the heat necessary for brazing are: Dipping the parts into a bath of the molten alloy, called dip brazing; heating by torches; furnaces; and by electrical resistance devices of various types.

In dip brazing the alloy is melted in a refractory container and covered with flux to prevent oxidation. The parts to be brazed are assembled in a suitable jig to hold them in position and dipped into the molten alloy. The size of the bath of the metal must be in proper proportion to the work. Heating may be done by any of the methods used with pot furnaces.

Another type of dip brazing which can be used is the salt bath type of furnace in which the articles to be brazed are immersed in the bath of molten salt, the parts having been previously assembled and the solder applied to the joint before immersing in the bath.

Different types of torches are used including air-gas, oxygen-gas, and oxy-acetylene. The high temperature of the oxy-acetylene flame allows rapid heating which is an advantage. A neutral or slightly reducing flame should be used in most cases, although for some types of bronze welding a slightly oxidizing flame is recommended.

Furnaces are used quite extensively for certain types of brazing. The brazing alloy is applied either along the joint or by inserts and the assembled parts introduced into the furnace. Furnaces with nonoxidizing atmospheres are preferable but if the joint is properly protected with flux, good work can be done in ordinary furnaces. The furnace should be large enough to allow the heating to be done rapidly and the temperature of the furnace should be considerably above the melting point of the brazing alloy.

The electrical resistance method is used on small parts or in those cases where a thin sheet of the brazing alloy can be inserted in the joint. It has the advantage of localizing the heat and works quickly.

Types of Brazing Alloys—The selection of the best brazing alloy depends upon many different factors. As the alloy must melt at a temperature below the melting points of the metals to be joined, the melting points of brazing alloys give a basis for three broad classifications:

Class I. Silver solders—Alloys having melting points ranging from 1200-1600°F.

Class II. Brass and nickel-silver brazing alloys—Alloys having melting points ranging from 1600-1700°F.

Class III. Copper alloy welding rods have melting points ranging from 1600-2250°F.

A general description of these three groups of alloys follows:

Table I
Silver Solders from A.S.T.M. Specification

Grade No.	Silver, %	Copper, %	Zinc, %	Cadmium, %	Impurities, % Max.	Melting Point, °F.	°C.	Flow Point, °F.	°C.	Color
1	10	52	38	a	0.15	1510	820	1600	870	Yellow
2	20	45	35	a	0.15	1430	775	1500	815	Yellow
3	20	45	30	5	0.15	1430	775	1500	815	Yellow
4	45	30	25	nil	0.15	1250	675	1370	745	Nearly white
5	50	34	16	nil	0.15	1280	695	1425	775	Nearly white
6	65	20	15	nil	0.15	1280	695	1325	720	White
7	70	20	10	nil	0.15	1335	725	1390	755	White
8	80	16	4	nil	0.15	1360	740	1460	795	White

*The addition not to exceed 0.50% of cadmium to assist in fabricating Grades 1 and 2 shall not be considered as harmful impurity.

Solders of Grades 1, 2, and 3 are suitable for brazing purposes which require a solder that flows more readily than the ordinary copper-zinc brazing solders. Grades 4 and 5 flow freely at a still lower temperature and are recommended for use where strong joints are required and in such cases where heating to a sufficiently high temperature to flow Grades 1, 2, or 3 would be injurious to the article being soldered. Grades 6, 7, and 8 are higher grade silver solders and are recommended for special cases where a high degree of malleability and ductility is required.

Silver Solders—Ternary alloys of silver, copper, and zinc in varying proportions have been used for many years as brazing alloys and are commonly called silver solders. The addition of silver to binary copper-zinc alloys lowers the melting point and a series of alloys can be made that will flow freely at temperatures from 1250-1600°F. In general, alloys having lower melting points contain relatively less zinc and high silver. Table I gives a list of the A.S.T.M. standard silver solders with the approximate melting points, flow points, and colors of grades.

Cadmium and tin are sometimes added to the ternary silver-copper-zinc alloys. Nickel, manganese, and chromium are also used but the standard alloys given in the A.S.T.M. specifications have been found to meet most of the requirements.

Silver solders are extensively used on practically all nonferrous metals and alloys and on steels and iron because of their strength, low melting points, free flowing properties, and resistance to corrosion. The strongest joints are made with small clearances, not over three or four thousandths of an inch for best results. Joints will stand severe shock and vibrations.

Borax or combinations of borax and boric acid are satisfactory fluxes except in the case of stainless steels when the addition of one of the alkali bifluorides or a halogen salt will prove beneficial. Fluxes that are fluid below 1400°F. are less likely to give trouble from inclusions, and particularly with the low melting point silver solders a great deal of the advantages in their use are lost if excessive superheat is required to keep the flux sufficiently fluid. By proper design and fitting of the joint, such a small amount of silver solder is required that although the cost of the silver solder may seem high, as compared to base metal solders, it has been found by experience that the cost of the finished joint will compare favorably with the base metal alloys in many cases.

The silver-copper-phosphorus eutectic melts at 1190°F. and a self-fluxing alloy* containing about 2.5% less phosphorus than the eutectic is used for brazing copper, brass and other nonferrous alloys. This alloy flows freely at a temperature of 1300°F., which is a most desirable property. Properly fitted joints have high tensile strength and are malleable. It can be rolled into thin gage sheet and drawn into fine wire. With brass and other alloys only a small amount of flux is required. Borax can be used as a flux but special fluxes which are more fluid than borax at 1300°F. are preferable.

In general, the use of silver solders should be considered where the higher temperatures required for other brazing alloys might cause excessive grain growth or damage to the metals to be joined and where strong ductile joints are necessary. They can be obtained in all sizes of wire and gages of sheet thus making it possible to obtain and apply them in the most convenient and economical form for use. They are also supplied in filings of different sizes.

Table II
Special Silver Solders

Grade No.	Silver, %	Copper, %	Zinc, %	Cadmium, %	Lead, %	Phos	Melt Point, °F.	Flow Point, °F.
1	5.00	.....	.....	Remainder	....	...	640	740
2	5.00	.....	16.60	78.40	..	...	480	600
3	5.50	.....	...	....	Remainder	....	579	715
4 ¹	2.50	0.25	...	....	97.25	....	568	668
5 ²	50.00	15.50	16.50	18.00	...	....	1160	1175
6 ³	15.00	80.00	.....	....	..	5	1190	1300

¹Proprietary Alloy, Westinghouse Electric & Mfg. Co.

²Proprietary Alloy, "Easy-Flo," Handy & Harman.

³Proprietary Alloy, "Sil-Fos," Handy & Harman.

Solders No. 1-4, inclusive, are used in those cases where strength is not an important factor but their higher melting range insures a greater margin of safety against failure at slightly elevated temperatures. In general, their other physical properties are more comparable to the standard soft solders. Solder No. 5 has the characteristics of the standard silver solders and strong joints can be made on nonferrous and ferrous metals and alloys, including stainless steel. The advantages of this solder are its low flow point and the strength of joint.

Brass and Nickel-Silver Brazing Alloys—Brass brazing alloys, quite generally known as "spelter solder" or "brazing solder" are alloys of copper and zinc in about equal proportions with smaller amounts of tin and nickel. These brazing solders are generally applied in powder or granulated form and melted by heating the several parts to be brazed to just about the melting point of the brazing solder, at which temperature the solder becomes fluid and runs readily between the contacting surfaces, alloying and bonding them together in a similar manner to soft and silver soldering. Dip brazing is also widely used. In this method the parts to be brazed are dipped into a molten bath of the brazing alloy, the parts having previously been suitably clamped together in the desired relative positions.

*Proprietary alloy under trade name Sil-Fos, Handy & Harman.

Table III
Brazing Alloys

Brazing Alloys	Melting Range, °F.	Copper, %	Zinc, %	Lead Max., %	Iron Max., %	Tin, %	Nickel, %	General Characteristics and Uses
A.S.T.M. 50-50 Grade....	1595-1620	50-53	Remainder	0.50	0.10	...	...	[Brass-yellow color. Used for strong connections on steel, cast iron, brass, bronze, nickel alloys for general brazing. Yellow to pale yellow color. Harder, stronger than A.S.T.M. grades. Gray to black color. Moderate strength. White color. Hard brazing alloy for nickel silver and nickel alloys. White color. Similar to above. Gray.]
A.S.T.M. 52-48 Grade....	1600-1620	52-53	Remainder	0.50	0.10	...	...
	1575	Remainder	45-50	....	....	3-5	...	
Black Button	1385-1440	Remainder	57-65	....	1	5-9	7-9	
White Brazing Alloys...	1600	Remainder	55-59	....	....	...	...
Phosphor-Copper*	1700	47	Remainder	....	....	...	11	
	1304-1526	93	(Remainder phos.)	....	....	...	...

*1304 is the liquidus and 1526 the solidus.

Table IV
Representative Copper Alloy Welding Rods

Alloy No.	Composition		Manganese	Copper	Melting Point, °F.	Remarks—Color, Name and Use
	Zinc	Tin				
1	38-43	0.50-1.50	.. .. .	Remainder	1625	Strong yellow bronze for general oxy-acetylene welds on steel, cast iron, copper, brass, bronze, and nickel alloys. Tobin bronze. Strength of approximately 50,000 psi. in tension. Distinctive yellow color.
2	38-43	0-1.5	0.05-0.75	Remainder	1600	Manganese bronze, quite similar to above except it is harder and more wear resisting than the Tobin bronze. Yellow bronze.
3	.....	Silicon 3-4	0.75-1.25	Remainder	1860	Silicon bronze, Everdur. High strength of approximately 50,000 lb. Applicable by oxy-acetylene torch to Everdur, copper, brass, bronze, nickel alloys and by the electric arc to Everdur, copper, bronze, and nickel. Pale red, characteristic bronze.
4	.....	Tin 2-10	Phosphorus 0.03-0.40	Remainder	1950-1830	The familiar phosphor bronze. Good strength, 40,000 psi., excellent wear resistance for higher tin and phosphor proportions. More frequently applied by means of the metallic or long carbon arc. Applicable to copper, bronze, brass, steel, and nickel alloys. Copper red to characteristic bronze color.
5	23-27	Nickel 15-19	Manganese 0.05-0.15	Remainder	1980	Wrought nickel silver. Nickel white color. Moderate strength 40,000 psi. Applicable only by oxy-acetylene or carbon arc torches. Used principally in welding similar base metals.
6	.....	Nickel 29-31	0.05-0.15	Remainder	2235	Cupro-Nickel 70-30. Nickel white color. Good strength, 50,000 psi. Applicable to white metals by oxy-acetylene torch or metallic arc. Covered electrode necessary for latter.
7	.....	.....	Phosphorus 0.03-0.09	Remainder	1980	Deoxidized copper. Used principally for welding copper by means of the oxy-acetylene torch. 28,000 psi. Copper red color.

There are many variations of compositions which may be used but the compositions given in Table III are quite representative of all types in common use. The general properties and uses are also indicated. The first two compositions listed correspond to A.S.T.M. Standard Specification B64-28.

Brazing solders are supplied in different grades, classified according to size and general shape of grain, known as "round grain", "long grain", and "lump". The latter is used primarily for dip brazing.

Fluxes for brazing alloys are in general the same as used for silver solders. Common borax used dry or mixed with water is used quite often but the water free powdered fused borax is preferable as it does not "crawl" away from the heat. Mixtures of boric acid and fused borax are also quite satisfactory. The fused borax fluxes should be mixed with commercial alcohol (water free) rather than water when a paste is desired.

The brazing operation may be carried out by heating with air, oxy-acetylene, oxy-hydrogen, or compressed air and gas torch, by furnace heating, or by carbon electric resistor placed against the work. In the dip process the heat comes from the bath although preheating in a furnace is often desirable.

In all except the dip brazing process the brazing alloy mixed with suitable amounts of flux is sprinkled or "painted" on the parts to be brazed before heating.

The phosphor-copper eutectic melts at approximately 1304°F. and contains 8.3% phosphorus. By lowering the phosphorus content to 7% or less, brazing alloys* are produced which can be used with copper and brass; the phosphorus in the alloy acting as a flux.

Copper Brazing is a term applied to the joining of steel when pure copper is used as the brazing alloy. The temperature must, of course, be above the melting point of copper (1980°F.). In copper brazing, the assembled steel parts with scraps of copper on the joints are most frequently placed in a furnace having a controlled hydrogen or other suitable atmosphere. Occasionally an oxy-hydrogen torch with excess hydrogen is resorted to.

Bronze Welding Rods—In addition to the two groups of alloys listed above, there is a third large group of ductile copper alloys which are, by reason of the welding methods employed in their applications, more properly termed welding rods.

These alloys are used: (1) where a moderately high strength (about 50,000 psi.) is required, (2) where good bearing or wear resistance is desired, (3) where the weld must possess some of the corrosion resistance characteristics of the base metal, or (4) where a color match is required, weld metal to base metal.

Welding Process—Though some of the yellow bronzes melt at a temperature only a few degrees higher than the 50:50 brazing alloys, the oxy-acetylene torch is quite generally used as a source of heat for welding rod and base metal.

With those welding rods which have little or no zinc in their make-up, the metallic or carbon arc may be used. The zinc from the yellow bronzes is volatilized too freely in the highly concentrated heat of the arc to admit of their being applied by the metallic or carbon arc.

Flux—Many good commercial fluxes for the high zinc bronzes are available. They are made up of various proportions of fused borax and boric acid.

These brazing fluxes are not entirely satisfactory for the silicon and the nickel alloys. An addition of sodium or lithium fluoride to the fused borax helps in the flowing of the silicon-copper alloys and the addition of a bifluoride to the fused borax base helps in preventing the formation of nickel oxide in the copper alloys.

In general, for connecting of cast iron, steel, copper, and nickel alloys where a color contrast is not objectionable, Alloy No. 1 in Table IV will be found most satisfactory. This alloy is without doubt the handiest and most nearly universal welding rod available for the repair shop and small manufacturer.

For high wear resistance surfaces Alloy No. 2, applied by the oxy-acetylene torch, or the 10% tin Phosphor Bronze, Alloy No. 4, applied by metallic or carbon arc, can be used.

For comparable corrosion resistance, select the welding rod which is nearest the composition of the base metal.

*Proprietary Alloy, "Phos-Copper," Westinghouse Electric & Mfg. Co.

Welding rod No. 3 is used for the most part in making fusion welds in a base metal of a similar composition by the use of the oxy-acetylene torch or the carbon or metallic arc. The base alloy is finding a wide application in the manufacture of hot water storage tanks and various vessels for the chemical industries.

Of the two white metals, Alloys No. 5 and 6, the former is used almost entirely on the nickel-silver alloys using the oxy-acetylene torch though it could be used on steel if the yellow of Alloy No. 1 were objectionable.

Alloy No. 6 is appropriate for use on the 70:30 Cupro Nickel base metal which is finding wide application in situations where a combination of strength and corrosion resistance is desired at elevated temperatures.

A word of caution should be given about the possibility of intercrystalline embrittlement of steel joints when brazing with brass or bronze brazing alloys. If the joint is heated above 2000°F. intercrystalline penetration of the brass into the steel may occur. For example, oxy-acetylene or arc welding of joints which have been brazed are likely to cause trouble and this practice should be avoided as far as possible.

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The Aluminum Industry

By Junius D. Edwards*

Aluminum as an element has only been known about 100 years, and its commercial history is comprised within the last 50 years. It is one of the principal metallic products of the electrochemical industry.

Occurrence—The principal ore of aluminum is bauxite. Bauxite comprises the hydrated oxides of aluminum, $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ and $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, together with associated impurities such as the oxides of iron, silicon, and titanium. Bauxite is produced by the weathering and alteration of aluminum silicate rocks, and is widely distributed the world around, usually in tropical and semitropical regions, where the weathering processes which have produced it have proceeded at an accelerated pace. At the present time, the principal supplies of bauxite come from France, the United States, Dutch Guiana, British Guiana, Hungary, Italy, and Jugo-Slavia. Bauxite is thus not a rare ore, and its principal value, when delivered in refined form for the electrolytic production of aluminum, lies in the transportation charges and chemical refining costs incident to its purification. The bauxites used for the production of aluminum contain about 55-65% alumina; it takes about 4 lb. of bauxite, therefore, to produce 1 lb. of aluminum. It has been estimated that there is enough bauxite in sight to supply the world with aluminum for the next 1,000 years.

Extraction or Refining Methods—In the electrolytic reduction of aluminum oxide, any impurities such as the oxides of iron, silicon, and titanium are reduced, along with the alumina. The alumina used is first refined, therefore, by removal of these impurities. It is essential to start with raw materials of the highest purity, and this includes not only the alumina but the carbon electrodes and the fused electrolyte employed in the process.

The Bayer process is almost universally employed for the purification of bauxite. In this process the bauxite is digested with caustic soda solution under pressure and the alumina dissolved out as a solution of sodium aluminate. The residue, known as red mud, contains the oxides of iron, silicon, and titanium, and is separated by filtration. Aluminum hydrate is separated from the solution of sodium aluminate by precipitation and is converted to the oxide, Al_2O_3 , by calcination.

The electrolytic reduction process is based on the discovery of Charles M. Hall, that molten cryolite dissolves alumina and that aluminum can be separated continuously from the molten solution at about 1000°C. by electrolysis. In operation, the electrolytic reduction takes place in large cells; they consist of a steel shell lined with carbon, forming an inner cavity in which the cryolite electrolyte is held. The carbon anodes, dipping into the electrolyte, introduce the current which separates the metallic aluminum electrolytically and provides the heat which keeps the bath liquid. Molten aluminum deposited on the bottom of the cell is withdrawn from time to time as it collects. This is the primary aluminum of commerce and will run in purity up to about 99.8%, depending upon the care and skill with which the raw materials have been prepared and the reduction process carried out. Aluminum of higher purity (up to 99.99%) can be produced by the Hoopes electrolytic refining process, in which aluminum is electrolytically dissolved from a molten aluminum-copper alloy anode and deposited in a layer of pure aluminum acting as cathode and floating on the molten electrolyte which separates the anode from the cathode layers. The production of a pound of aluminum requires about 10 kw-hr. of electrical energy, so that cheap electric power is essential for its commercial production.

Principal Products—The aluminum sheet of commerce, designated 2S by the principal producer, has a nominal purity of about 99.2%. It is, in fact, an alloy with small amounts of iron and silicon, and its strength is substantially increased thereby. Another commonly used wrought alloy, known as 3S, contains 1.25% of manganese. The principal elements used in the production of aluminum alloys are copper, silicon, manganese, magnesium, and zinc. Since the invention of duralumin and the discovery and explanation of heat treatment effects in aluminum alloys, a series of heat treatable aluminum alloys have been developed. They are frequently referred to as the "strong alloys of aluminum" and greatly extend the field of application of aluminum.

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Uses—Aluminum and its alloys can be worked and fabricated by the usual metal working processes such as rolling, stamping, spinning, drawing, extruding, and forging, and produced in the form of castings by the sand, permanent mold, or die casting processes. Except for magnesium and beryllium, aluminum is the lightest of the structurally useful metals. In the transportation field, it is not only the lightness of aluminum and its alloys, but the high physical properties obtainable by alloying and heat treating which make it suitable for light weight structures.

Aluminum has good electrical conductivity; volume for volume, its electrical conductivity is about 61% that of copper, and weight for weight, its conductivity is about 200% that of copper. High electrical conductivity, combined with good weather resistance and adequate physical properties, accounts for its use in over 700,000 miles of aluminum cable, steel reinforced.

Aluminum is also a good conductor of heat. This property is made use of in such varied applications as cooking utensils, and pistons and cylinder heads for internal combustion engines.

Aluminum is a good reflector for radiant energy throughout the spectral range, from ultra-violet through the visible range and into the infra-red. It is being employed in thin films on the reflectors of the most modern telescopes, is widely used for light reflectors in the illuminating industry, and its high reflectivity for infra-red radiation is giving it a unique field of usefulness for thermal insulation. As a practical light reflector, its usefulness has been extended by the Alzak process, which includes electrolytic brightening to develop maximum reflection, coupled with an electrolytic oxide coating to provide a glass-like, transparent, weather resistant and cleanable surface. In the thermal insulation field, aluminum foil,

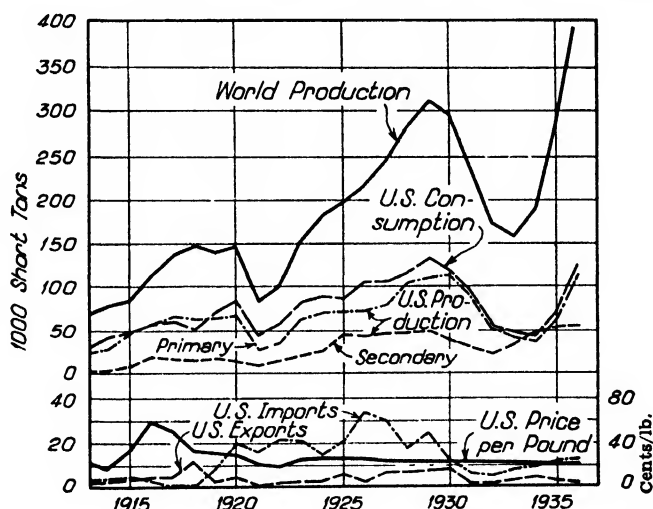


Fig. 1—Primary aluminum produced in the United States and in the world, 1913-1936, compared with imports into the United States and with domestic consumption, exports, secondary production, and the trend of the average New York quoted price (No. 1 virgin ingot, 98-99%). Courtesy of Bureau of Mines, Minerals Yearbook, 1937.

with its high reflectivity for thermal radiation and its low radiating power or emissivity for the same type of radiation, gives to a structure comprising sheets of aluminum foil separated by air spaces, a high insulating effect.

Aluminum forms, in contact with moist air, a thin, impervious film of oxide which protects it against further attack. It can be electrolytically oxidized to give it a thicker oxide film of great hardness and resistance to corrosion. These oxide films can be colored by the absorption of dyes or by impregnation with inorganic pigments.

Aluminum has a high heat of combustion, and this affinity for oxygen is the basis of the Thermit welding process, where reaction between finely divided alumi-

num and metallic oxides, such as iron oxide, produces a molten ferrous alloy at a high temperature.

Another chemical use of aluminum is as a deoxidizer in the manufacture of iron and steel. Its affinity for oxygen is so great that it is used in producing gas-free steel ingot.

Aluminum in finely divided flake-like form, supplied either as aluminum powder or aluminum paste, makes an excellent paint pigment. Aluminum paint made with this pigment forms a durable and protective paint for both metal and wood. It is relatively impervious to moisture penetration; is opaque to sunlight, hides and covers well, and maintains this protection over extended periods, even under conditions of severe exposure.

Statistics—The uses of aluminum and its alloys are being expanded as research develops a sound basis of fundamental knowledge regarding its physical, chemical, and engineering properties. During the last decade, the applications of aluminum in the U. S. have been along the following principal lines:

Percentage of Aluminum Used in Various Industries

Transportation (land, air, and water) ..	38%
Electrical conductor	16%
Cooking utensils	14%
Machinery and electrical appliances.....	9%
Iron and steel metallurgy.....	8%
Building construction	4%
Miscellaneous foundry and metal working.....	4%
Chemical	2%
Food and beverages.....	2%
General miscellaneous	3%

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Constitution of Aluminum-Chromium Alloys

By W. L. Fink* and H. R. Freche*

A few commercial aluminum alloys contain small amounts of chromium, but substantial amounts of chromium increase the liquidus temperature beyond commercial limits. Consequently, the extreme aluminum-end of the system is of greatest interest.

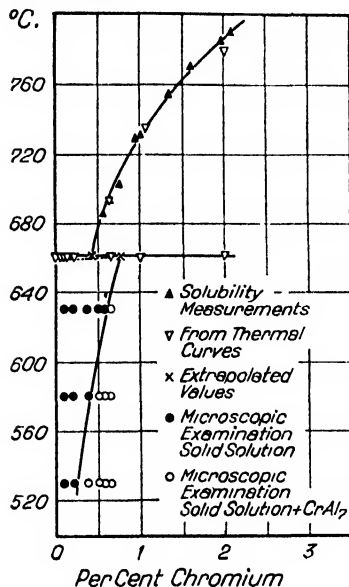


Fig. 1—Aluminum end of the Aluminum-Chromium Constitution Diagram.

of sodium hydroxide at 70°C. darkens the constituent. When etched with 0.5% hydrofluoric acid, the constituent is outlined but does not change in color.

Leon Guillet¹ studied aluminum alloys containing from 65-90% chromium. He observed the two intermetallic compounds AlCr and AlCr_2 in this concentration range. According to Hindrichs² aluminum and chromium form an intermetallic compound AlCr , which corresponds to 85.2% chromium. Goto and Dogane,³ in their paper on the aluminum-chromium alloys, suggested the intermetallic compound CrAl .

In a recent investigation by Fink and Freche⁴, on the aluminum-end of the aluminum-chromium diagram, alloys were used which contained 0.02% iron and 0.01% silicon and 0.01% copper. The results of the investigation are illustrated by Fig. 1. At the aluminum-end of the system, the intermetallic compound CrAl , which contains 21.60% chromium and 78.40% aluminum, was identified. At 661°C. a peritectic reaction occurs between CrAl and a melt, containing 0.41% chromium, to form a solid solution containing 0.77% chromium. The solid solubility decreases with temperature; and at 530°C. the saturated solid solution contains only 0.25% chromium.

In aluminum-rich alloys, the unetched chromium constituent appears gray when illuminated by the light from a carbon arc filtered through a 78A Wratten filter. A 10% solution of sodium hydroxide at 70°C. darkens the constituent. When etched with 0.5% hydrofluoric acid, the constituent is outlined but does not change in color.

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Constitution of Aluminum-Copper Alloys

By E. H. Dix, Jr.* and H. H. Richardson†

The aluminum-rich alloys of the aluminum-copper system are of great commercial importance in both wrought and cast forms. The wrought alloys generally do not contain over 5% copper, although the cast alloys may contain as much as 12-15% copper. With further increase in copper content the brittleness of the alloys is too great to permit more than a few special commercial applications. Both the wrought and cast alloys are subject to improvement in strength and hardness by heat treatment.

Because of the commercial importance of the aluminum-copper alloys the constitution of this system has been the subject of a number of independent researches. At the aluminum end of the series an intermediate aluminum-copper solid solution forms a eutectiferous series with aluminum in which the eutectic alloy contains 33% copper and melts at 548°C. At the eutectic temperature 5.65% copper is soluble in solid aluminum and this amount decreases to less than 0.5% at room temperature. The susceptibility of the aluminum-copper alloys to improvement in strength by heat treatment depends on this decrease in solubility.

The diagram of Fig. 1 is according to the most recent work of Stockdale,¹¹ but modified in the composition range shown in the insert to agree with the investigation of Dix and Richardson.⁷ The present diagram of Stockdale differs, in the range shown, from an earlier diagram⁸ in that a solid solution region from 52.5-53.9% copper is shown in place of the intermetallic compound CuAl₃. The more recent

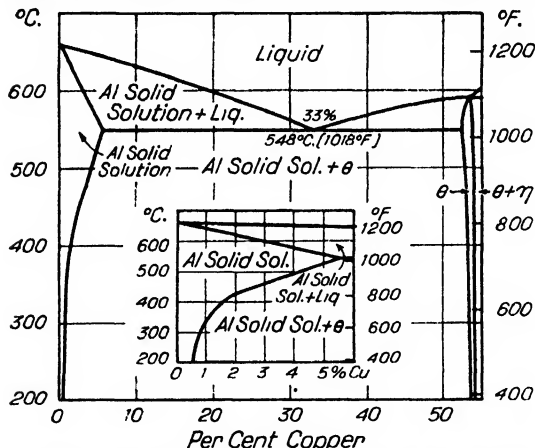


Fig. 1—Aluminum-Copper Constitution Diagram (Stockdale, Dix, and Richardson).

type to improvement in strength and hardness by heat treatment.

The solubility data shown in the following tabulation and the insert of Fig. 1 were arrived at by microscopic examination of alloys of extremely high purity, which had been annealed for long periods of time:

Saturation Limit of Copper in Solid Aluminum According to Dix and Richardson

Temperature, °C.....	200	300	350	400	450	500	548
Per cent copper.....	0.50	0.70	1.00	1.50	2.60	4.10	5.65

These results are in fair agreement at the eutectic temperature with the result obtained by Rosenhain⁹ at the National Physical Laboratory and at 300°C. with that of Merica¹ at the U. S. Bureau of Standards. They also agree with the results obtained by Ohtani and Hemmi¹⁰ who used electrical resistivity measurements for a limited temperature range of 420-520°C. The solubility at 200°C. was obtained on chill cast specimens annealed at that temperature for two weeks subsequent to

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a homogenizing treatment of 11 days at 540°C. The more recent results of Stockdale for the limited range from 460-530°C. are in agreement with the above values.

The θ phase, when it occurs in the light aluminum alloys, polishes slightly in relief and has a marked tendency to tarnish. However, if carefully polished it is clear and almost colorless, with a slightly pink tinge. Its most striking characteristic is the way in which it lights up in passing out of focus. A light etch with 0.5% hydrofluoric acid leaves this constituent clear with a well defined boundary. It is colored brown or black by immersion for 40 sec. in 25% nitric acid at 70°C., followed by quenching in cold water.

The solid solution of copper in aluminum has been shown by X-ray analysis^{4, 9, 10} to have a face centered cubic lattice similar to that of pure aluminum. Solution of copper is effected by simple substitution with a contraction of the lattice. The θ phase or the so-called CuAl, has been shown by X-ray analysis^{4, 9} to have a body centered tetragonal structure with an axial ratio of 0.805.

See page 1342 for a discussion of the copper end of this diagram.

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Constitution of Aluminum-Iron Alloys

By E. H. Dix, Jr.*

Iron is always present in aluminum of commercial purity and even the highest purity electrolytically refined aluminum (99.95% Al) contains visible particles of an iron constituent. In the commercial aluminum alloys, iron is often found in complex constituents containing aluminum and one or, perhaps, more of other elements such as silicon, manganese, or copper. Two ternary aluminum-iron-silicon constituents have been definitely identified.

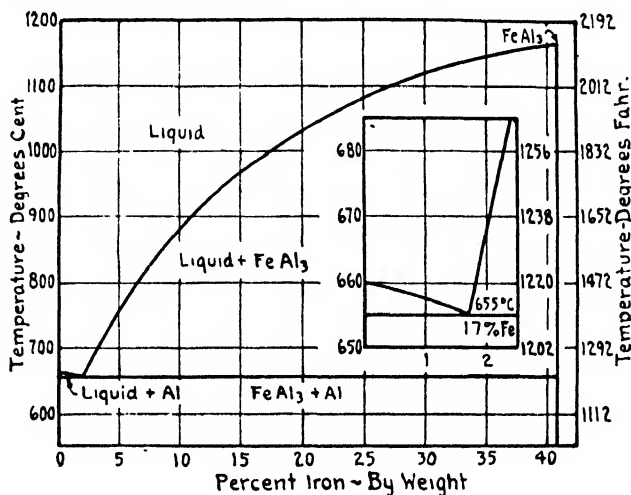


Fig. 1—Aluminum-Iron Constitution Diagram (Gwyer, Phillips, and Dix).

In aluminum substantially free from other elements, iron occurs as the aluminum-iron compound, FeAl_3 . As shown by the diagram, Fig. 1, aluminum and FeAl_3 form a simple eutectiferous series. Reliable investigations have placed the eutectic concentration at 1.7-2.5% iron and the temperature at 648-655°C. These differences are probably caused by variations in the purity of the aluminum used and the pronounced tendency of the alloys to undercool.

The figures indicated in the insert, showing the eutectic region, of Fig. 1 were obtained on aluminum of very high purity (impurities other than iron less than 0.03%). The iron content of the eutectic was obtained by chemical analysis of very slowly cooled specimens, which were shown by microscopic examination to have a eutectic structure. However, by rapid cooling from a high temperature a fine structure having the appearance of a eutectic was found with iron as high as 3.5%. The eutectic temperature was determined from a consideration of a number of heating and cooling curves of the same high purity material.

FeAl_3 is practically insoluble in solid aluminum, although fine particles of eutectic FeAl_3 exhibit marked coalescence after an extended annealing just under the eutectic temperature.

In a properly polished specimen particles of FeAl_3 appear bright with a slightly purple tinge. Swabbing with 0.5% hydrofluoric acid slightly attacks the aluminum solid solution and so removes any slight surface flow, and if not carried too far the FeAl_3 retains its characteristic bright purplish color.

FeAl_3 is colored black by 30 sec. immersion in a 20% solution of H_2SO_4 at 70°C., followed by quenching in cold water. However, the iron-silicon-aluminum constituents are also attacked by this reagent, although the appearance after etching is different. A similar procedure with 25% HNO_3 is useful in differentiating between these constituents.

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†Eutectic Temperature.

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Constitution of Aluminum-Manganese Alloys

By E. H. Dix, Jr.,* W. L. Fink,* and L. A. Willey*

Introduction—Manganese is used in relatively small amounts in a number of commercial aluminum alloys. In these alloys, the manganese occurs in a complex aluminum-manganese constituent in which atoms of iron or other elements have replaced a part of the manganese atoms. Chemical analysis of such constituents separated from aluminum-iron-manganese alloys has shown as much as 1 atom of iron to 2 atoms of manganese. The presence of iron, even in small amounts, in the constituents greatly alters their solubility. Consequently it is very difficult to prepare alloys of sufficient purity to be classed as binary alloys. Most of the results found in the literature were obtained from alloys that contained a considerable quantity of silicon, iron, and copper as impurities, and, therefore, really apply to complex systems.

Constitution Diagram—Krings and Ostmann¹ in their work on the aluminum-copper-manganese alloys assigned the formula $MnAl_4$ to the compound at the aluminum end of the binary system. They found the eutectic between this compound and aluminum at 649°C. and 3% manganese. Rassow² found a eutectic temperature of 650°C. He assigned the formula $MnAl_4$ to the compound at the aluminum end of the system and interpreted a thermal arrest occurring at 670°C. as a polymorphic transformation of that compound. Bradley and Jones,³ through X-ray analysis of annealed aluminum-manganese alloys, also concluded that the aluminum-rich compound was $MnAl_4$. The diagram of Ishiware⁴ shows that a compound $MnAl_4$ reacts with the melt at 670°C. to form the compound $MnAl_6$. Bosshard⁵ determined the solid solution range at the aluminum end of the system but his values are lower than those for binary alloys because his samples contained large amounts of impurities.

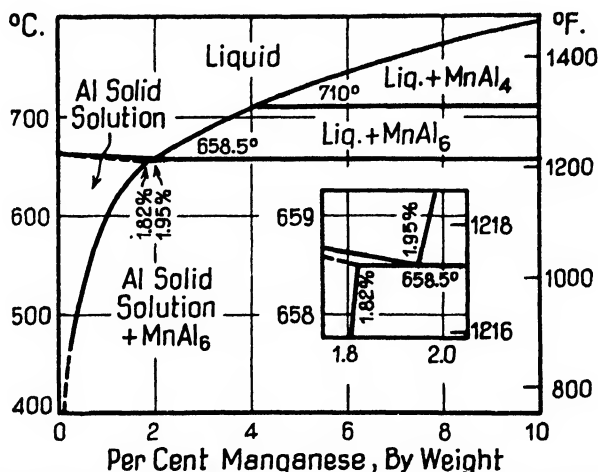


Fig. 1—Aluminum-Manganese Constitution Diagram (Dix, Fink, and Willey).

In a recent investigation by Dix, Fink, and Willey⁶ alloys were used which contained less than 0.01% each of iron, silicon, and copper. It seems probable that such small amounts of impurities would not substantially alter the results and that the diagram shown in Fig. 1 is a close approximation to the true binary diagram.

At the extreme aluminum end of the system the intermetallic compound $MnAl_4$, containing 25.35% manganese, forms a eutectic with an aluminum-manganese solid solution. This eutectic occurs at 1.95% manganese and 658.5°C. The solid solubility of manganese in aluminum decreases from 1.82% at the eutectic temperature to 0.36% at 500°C. The compound $MnAl_4$ decomposes at 710°C. to

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form the compound $MnAl$, containing 33.7% manganese and liquid aluminum containing 4.06% manganese in solution.

In aluminum-rich alloys, the unetched constituent $MnAl$, has a flat gray appearance. A solution containing 1% sodium hydroxide etches this constituent to a blue gray color in about 10 sec. at room temperature. A 10% solution of sodium hydroxide at 70°C. etches the compound dark brown to black. When etched with 0.5% hydrofluoric acid, the compound is outlined, but does not change color unless iron is present, in which case the constituent turns brown or black.

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Constitution of Aluminum-Nickel Alloys

By Wm. L. Fink* and L. A. Willey*

Several of the complex commercial alloys of aluminum contain nickel as one of the alloying elements. Although the pure binary aluminum-nickel alloys are not important from a commercial standpoint, a knowledge of the constitution of the system is a prerequisite for the study of the more complex commercial alloys.

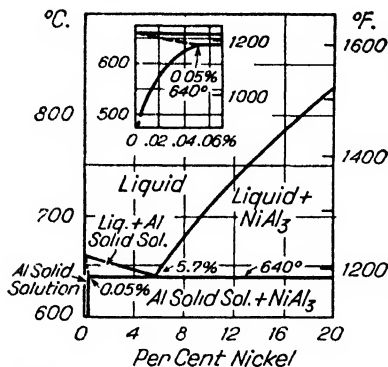


Fig. 1—Aluminum-Nickel Constitution Diagram (Fink and Willey).

solid solution form a eutectic at 5.7% nickel and 640°C. The insert of Fig. 1 shows the solubility curve in detail. The limit of solid solubility decreases from 0.05% nickel at the eutectic temperature to approximately 0.005% at 500°C.

Although the solubility in the solid state is slight, the binary alloys containing a few hundredths of a per cent of nickel have relatively high susceptibility to age hardening. The maximum hardness for such alloys is obtained by heat treating at about 630°C. followed by artificially aging at about 265°C. for 8 hr.

The compound NiAl_3 , occurring in the binary alloys, appears under the microscope as a light gray constituent with a slightly purple tinge in the unetched condition. Keller and Wilcox,⁵ investigating the etching characteristics of constituents of aluminum alloys, found that the NiAl_3 constituent is colored brown to black in an aqueous solution of 0.5% HF . They observed that about the same coloration is obtained using an etching reagent of 10% NaOH at 70°C., or one containing 0.5% HF , 1.5% HCl and 2.5% HNO_3 . A 25% HNO_3 solution at 70°C. does not color or attack the constituent.

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Constitution of Aluminum-Silicon Alloys

By E. H. Dix, Jr.,* and A. C. Heath, Jr.†

Introduction—Silicon, inevitably present in even the purest grades of aluminum, was at one time believed detrimental to the properties. Extended studies of the binary aluminum-silicon alloys disclosed the value of the element, so alloys containing up to about 13% silicon are now widely used; especially as casting alloys.

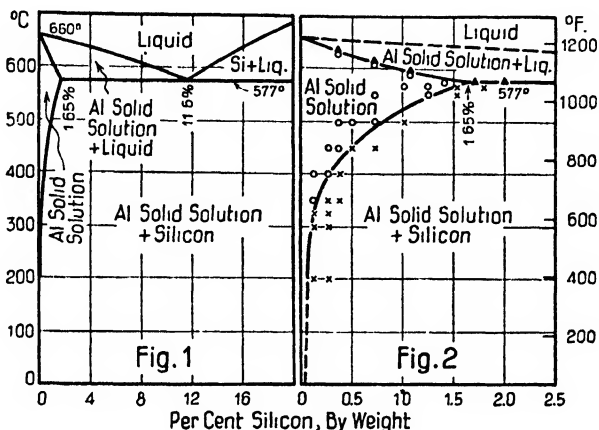


Fig. 1—Aluminum-Silicon Constitution Diagram (aluminum end). Location of eutectic by Edwards, and the liquidus curves by Gwyer and Phillips.

Fig. 2—Aluminum-Silicon Constitution Diagram (aluminum end), by Dix and Heath.

Studies of the binary aluminum-silicon system have been generally somewhat confused by the presence of iron, which produces a highly complex system, but by the use of very pure material these effects can be minimized.

Constitution Diagram—The results of early work on the system are in fairly good agreement and show it to be a simple eutectiferous system without compounds. Probably the most satisfactory determinations of the eutectic temperature (577°C) and composition (11.6% Si) are those of Edwards¹ and Gwyer and Phillips.² Alloys containing as high as 14% silicon may be caused to solidify without the separation of visible particles of primary silicon by either rapid cooling³ or the presence of "modifiers"⁴ such as sodium. This undercooling or modification produces some changes in the alloy structure which are accompanied by marked changes in physical properties. In addition, it lowers the apparent eutectic temperature from 577 to as low as 564°C.

A diagram of the aluminum end of the system is shown in Fig. 1. Dix and Heath,⁵ using thermal and microscopic methods on samples made from high purity aluminum and silicon, have more recently investigated the aluminum end of the system. Their diagram for this area is given in Fig. 2.

The identification of silicon particles under the microscope is comparatively simple as long as they are of fair size, since they can be recognized by their purple or slate color in the unetched condition. When polished with magnesia using the proper pressure they will appear flat in the matrix, but if too light pressure is used they will stand in relief and may become faded or discolored so that identification by color is not reliable. The particles are remarkably resistant to most etching reagents so the general effect of etching will be to remove surface flow and outline the constituent. A light etch with a ½% aqueous solution of hydrofluoric acid will produce this particle definition, but may somewhat discolor the constituent.

The solid solubility determinations by Dix and Heath on very pure alloys, are

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¹U. S. Patent 1,387,900 and 1,410,461.

²U. S. Patent 1,572,459.

not greatly different from those of Gwyer and Phillips and those obtained by a chemical method by Köster and Müller.⁴

Temperature Solubility Limits

(By Dix and Heath)

Temperature, °C.	577*	550	500	450	400	350	300	200
Saturation limit, % Si.....	1.65	1.30	0.80	0.48	0.29	0.17	0.10	0.05

*Eutectic temperature.

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Constitution of Aluminum-Titanium Alloys

By W. L. Fink* and K. R. Van Horn†

Introduction—Titanium commonly occurs in small quantities in many of the aluminum ores, and traces of titanium oxide not removed during the purification of the ore are reduced with the alumina. In this manner traces of titanium are sometimes unavoidably present in aluminum pig. Larger percentages of titanium are sometimes introduced into aluminum alloys, but it is not usually added as a major alloying element.

Constitution Diagram—The little attention which the aluminum-titanium constitution diagram has received has been restricted to the aluminum end of the system. E. van Erckelens,¹ Manchot and Leber,² and Fink, Van Horn and Budge³ have published constitution diagrams; while Wohler,⁴ Manchot and Richter,⁵ and Weiss and Kaiser⁶ described the compound existing in aluminum-rich alloys.

The liquidus, which represents the solubility curve of the aluminum-titanium constituent, $TiAl_3$, in molten aluminum, has a steep slope^{1, 2, 3} and attains a temperature of about $1350^{\circ}C.$ at 37.2% titanium ($TiAl_3$). The liquidus values of E. van Erckelens and Manchot and Leber are in agreement at the higher titanium contents, but vary appreciably at the extreme aluminum (commercial) end. Fink, Van Horn and Budge observed that the primary thermal effects in specimens of low titanium content were weak and susceptible to decided under-cooling. Therefore, these investigators determined the liquidus by a different procedure—analysis of the supernatant melt in equilibrium with precipitated $TiAl_3$. The data thus obtained are incorporated in the accompanying diagram (Fig. 1) which shows that the liquidus intersects the peritectic horizontal at $665.1^{\circ}C.$ and 0.18% titanium.

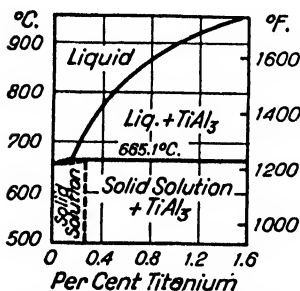


Fig. 1—Aluminum-Titanium Constitution Diagram.

Two thermal arrests have been observed³ in alloys containing over 0.03% Ti. Above 0.18% Ti these arrests occur at $665.1^{\circ}C.$ and $659.8^{\circ}C.$ respectively, while below 0.18% Ti the two points converge and meet at the melting point of pure aluminum. The lower arrest may be interpreted as the failure to obtain equilibrium during the cooling curve experiment. As chemical and X-ray analyses revealed only one compound, $TiAl_3$, some solid solubility would be necessary to explain the peritectic arrests at $665.1^{\circ}C.$ A solid solubility of approximately 0.28% titanium in aluminum at $500-650^{\circ}C.$ was determined by electrical conductivity measurement and microscopic observations. It is not definitely known whether the solubility is constant over this range or whether the rate of diffusion is so slow that equilibrium is not realized. The horizontal line at $665.1^{\circ}C.$ therefore represents the peritectic reaction $TiAl_3 + \text{liquid} = \text{aluminum solid solution}$.

Microscopic examination of binary aluminum-titanium alloys reveals the titanium phase in the form of large needles which are cross sections of plates. The constituent appears to be blue-gray in an unetched polished section. Early chemical methods gave $TiAl$, $TiAl_2$, and Ti_2Al_3 as the formula of the Al-Ti compound. Recent determinations have definitely established the formula $TiAl_3$, the crystal structure of which has been analyzed⁷ and found to be tetragonal.

$$a_0 = 5.424$$

$$c_0 = 8.574$$

$$\frac{c_0}{a_0} = 1.58$$

Four molecules or 16 atoms per unit cell

Space group (4d 8 — a, b, c, d)

Closest approach of atoms Al-Al = 2.875

Closest approach of atoms Ti-Ti = 3.835

Closest approach of atoms Al-Ti = 2.712

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Constitution of Aluminum-Magnesium Silicide Alloys

By E. H. Dix, Jr.,* F. Keller,* R. W. Graham†

General—The addition of magnesium and silicon to aluminum results in a type of strong alloy which is of considerable commercial importance. The alloys are readily workable in the annealed form and may be strengthened and hardened by a solution heat treatment. The maximum strength and hardness are obtained by a precipitation heat treatment following the solution heat treatment. The susceptibility of these alloys to heat treatment is attributed to the presence of the magnesium and silicon in the form of the compound Mg_2Si .

An extensive investigation of the constitution of aluminum alloys containing various amounts of magnesium and silicon was made by Hanson and Gayler.¹ Part of their investigation consisted of determining the solid solubility of the compound Mg_2Si in aluminum.

Constitution Diagram—In the system of aluminum, magnesium and silicon all alloys lying on the base line running from the aluminum corner of a triangle representing the ternary alloys to the point representing the compound Mg_2Si form a simple eutectiferous series. Mg_2Si forms a eutectic with aluminum at about 13% of the compound. The eutectic temperature has been found to be 595°C.

It has been generally assumed that the precipitate formed at low temperatures from the solid solution of magnesium and silicon is Mg_2Si . However, Mehl, Barrett,

and Rhines² were unsuccessful in their attempt to find evidence of the Mg_2Si lattice in their X-ray studies to identify the precipitate. Their results indicated that the compound $AlMg_2$, $(\beta Al-Mg)^3$ was present while the presence of Mg_2Si and silicon was less certain.

When a properly polished specimen is examined the compound Mg_2Si appears pale blue in color, but it readily tarnishes to a deep iridescent blue. The compound is readily attacked by water in the polishing operation which makes the preparation of samples somewhat difficult.

Etching is not desirable for identification of the constituent since all of the etching reagents commonly employed for aluminum alloys attack the compound Mg_2Si and remove its characteristic deep blue

color. However, a 0.5% solution of hydrofluoric acid in water is generally used for removing surface flow and for revealing fine particles and grain size.

The constitution of the aluminum-magnesium silicide alloys containing up to 19% of the compound Mg_2Si is shown in Fig. 1. This diagram is taken from the work of Hanson and Gayler and has been modified to include the more recently determined solubility limits.⁴ The solubility limits for Mg_2Si for various temperatures are also given in the following tabulation:

Temperature Solubility Relations

Temp., °C.	595*	500	400	300	200
Saturation limit (% Mg_2Si).....	1.85	1.05	0.53	0.30	0.27

*Eutectic temperature.

These solubility relations hold true only when the magnesium and silicon are present in the proper proportions to form the compound Mg_2Si . An excess of magnesium over that required to form the compound reduces the solubility in proportion to the amount of excess magnesium present. An excess of silicon does not affect the solubility of Mg_2Si in aluminum.

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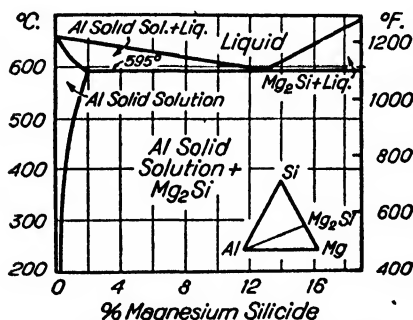


Fig. 1—Partial diagram of the aluminum-magnesium silicide system (Hanson and Gayler with modified solubility curves by Dix, Keller, and Graham).

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Constitution of Aluminum-Magnesium-Zinc Alloys

By W. L. Fink* and L. A. Willey*

The ternary system, aluminum-magnesium-zinc, is of particular interest because useful alloys are found in all three corners of the diagram.

The three binary diagrams are shown in Fig. 1, 2, and 3. The doubtful and extrapolated portions of the binary diagrams are shown with dotted lines. The

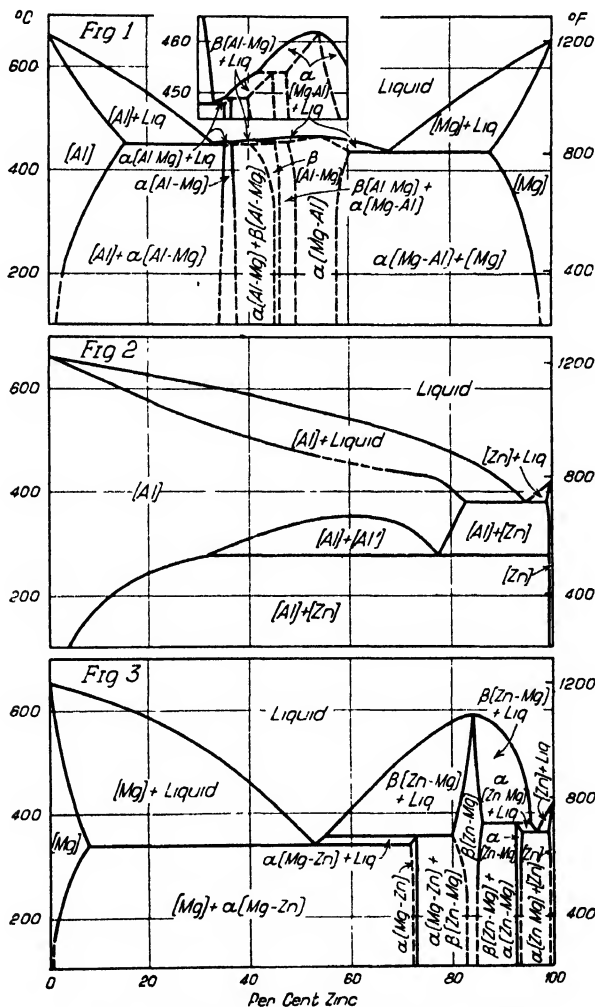


Fig. 1—Aluminum-magnesium constitution diagram.

Fig. 2—Aluminum-zinc constitution diagram.

Fig. 3—Magnesium-zinc constitution diagram.

solid lines of the diagrams were taken from various investigations which are in substantial agreement. In the binary systems as well as in the ternary system, the phases have been designated by a modification¹ of the method proposed by Dix and Keith.² A phase is designated by placing in parentheses the chemical symbols of the elements essential to the formation of that phase. The symbols

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in the parentheses are separated by dashes in order to clearly distinguish them from a chemical formula. Elements that are not necessary to the formation of the phase in question, but which may be present in solid solution, are not indicated in the designation. The symbols are placed in the order of the atomic percentage

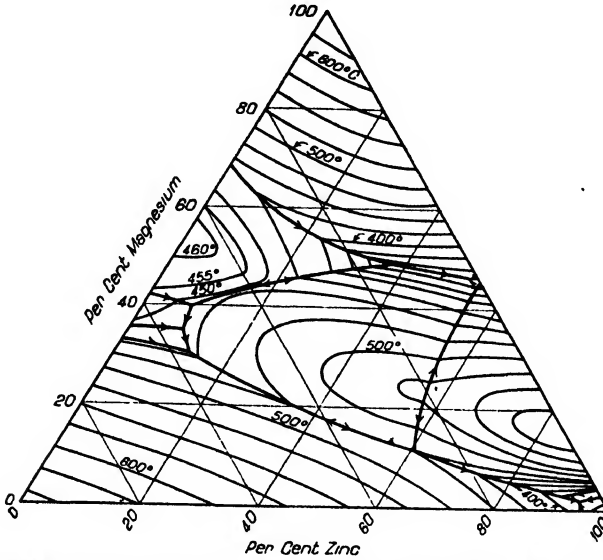


Fig. 4—Liquidus surface, aluminum-magnesium-zinc constitution diagram (Köster, Wolf and Dullenkopf).

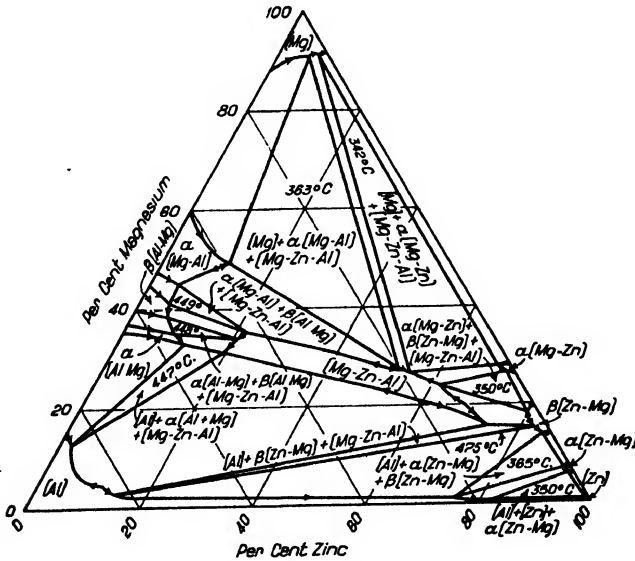


Fig. 5—Solidus surface, aluminum-magnesium-zinc constitution diagram (Köster, Wolf, Dullenkopf, Fink and Willey).

of the elements. If two or more phases would have the same designation according to these rules, they are distinguished by prefixing Greek letters. A list of all the phases found in the aluminum-magnesium-zinc system is given below, together with other symbols which have been used in the literature to designate these phases:

(Al) = Al, Aluminum solid solution, α , β , γ
 $\alpha(\text{Al-Mg})$ = Al_2Mg , Al_3Mg_2 , β
 $\beta(\text{Al-Mg})$ = AlMg , γ
 $\alpha(\text{Mg-Al})$ = Mg_2Al , Mg_3Al_2 , γ , δ
 (Mg) = Mg , Magnesium solid solution, α , δ , ξ
 $\alpha(\text{Mg-Zn})$ = MgZn , ζ
 $\beta(\text{Zn-Mg})$ = Zn_2Mg , η , γ
 $\alpha(\text{Zn-Mg})$ = Zn_5Mg , δ , β
 (Zn) = Zn , Zinc solid solution, α
 (Mg-Zn-Al) = T , $\text{Mg}_2\text{Zn}_3\text{Al}$, $\text{Mg}_5\text{Zn}_{10}\text{Al}_3$

[illegible]

¹M. Hamasumi, Complete Equilibrium Diagram of the System Aluminum-Magnesium-Zinc, Sci. Repts., Tohoku Imp. Univ., 1936, First Series, K. Honda Anniversary Volume, p. 748.

Physical Constants of Aluminum

By Junius D. Edwards*

Introduction—Aluminum having a purity as high as 99.99% has only been available since the development of the Hoopes process of electrolytically refining aluminum. Previously the physical constants of aluminum were of necessity determined with metal of lower commercial purity. However, there are now available data on most of the properties of the very pure electrolytically refined aluminum. In the discussion an effort will be made to indicate the effect on the property in question of the impurities (iron, silicon, and copper) ordinarily present in commercial aluminum.

Atomic Weight—The element aluminum has the atomic number 13. Its atomic weight is 26.97 according to the present accepted value. No isotopes of aluminum are known.

Crystal Form—Aluminum, like most of the ductile metals, crystallizes in the face-centered cubic lattice. The unit edge of the lattice cube is 4.0413×10^{-8} cm. as determined on high purity aluminum.^{1, 2}

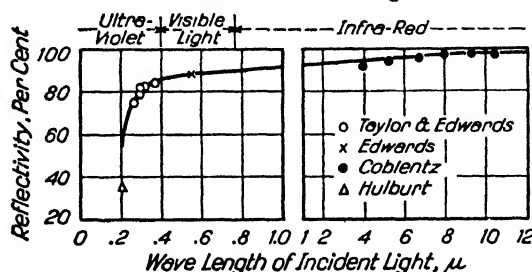


Fig. 1—Reflectivity of aluminum for radiation of various wave lengths.

Density—Aluminum (99.971% purity) has a density of 2.6989 g. per cc. at 20°C. when in the cold rolled condition and 2.6996 g. per cc. after annealing. As with most of the metals, the density is slightly decreased by cold working and increased by subsequent annealing.³ The addition to aluminum of heavy metals, such as iron, copper, and zinc, increases the density. Silicon

(density = 2.4) in amounts up to about 0.3% slightly increases the density of aluminum and thereafter decreases it.

Typical values for the density of aluminum for the temperature range of 20–1100°C. are given in Table I. The values for density are numerically equal to the specific gravity of the metal when referred to the weight of water at 4°C. The values for density (g. per cm.³) may be converted into the weight in lb. per cu.ft. by multiplying by the factor 62.428. Aluminum at 70°F. weighs approximately 168.6 lb. per cu.ft. (2.70×62.428). Data for aluminum of three different grades are given in the table.⁴ In passing from the liquid to the solid state at the freezing point, there is a contraction in volume amounting to 6.6%.

Table I

Density of Aluminum

According to J. D. Edwards

Temp.	Condition of Metal	Density—g. per cc.		
		99.75% Aluminum	99.4% Aluminum	98.25% Aluminum
Centigrade Temperature Scale				
20	Solid	2.703	2.706	2.727
100	Solid	(2.69)	.....	.....
200	Solid	(2.67)	.....	.....
400	Solid	(2.62)	.....	.....
658.7	Solid	(2.55)	.....	.....
658.7	Liquid	2.382	2.384	2.405
700	Liquid	2.371	2.373	2.394
800	Liquid	2.343	2.345	2.366
900	Liquid	2.316	2.318	2.339
1,000	Liquid	2.289	2.291	2.311
1,100	Liquid	2.262	2.264	2.285

Note—Values enclosed in parentheses are calculated from expansion formula.

(Continued)

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Temp.	Condition of Metal	Density—g. per cc.		
		99.75% Aluminum	99.4% Aluminum	98.25% Aluminum
Fahrenheit Temperature Scale				
68	Solid	2.703	2.706	2.727
1,217.7	Solid	(2.55)	.....	.....
1,217.7	Liquid	2.382	2.384	2.405
1,300	Liquid	2.369	2.371	2.393
1,400	Liquid	2.354*	2.356	2.377
1,500	Liquid	2.339	2.341	2.362
1,600	Liquid	2.324	2.326	2.347
1,700	Liquid	2.309	2.311	2.332
1,800	Liquid	2.294	2.296	2.316
1,900	Liquid	2.278	2.280	2.301
2,000	Liquid	2.263	2.265	2.286

Note—Values enclosed in parentheses are calculated from expansion formula.

Note—Values enclosed in parentheses are calculated from expansion formula.

Compressibility—The compressibility or percentage change in volume with unit change in pressure of 1 megabar (0.987 atmospheres; 14,504 psi.) of electrolytically refined aluminum is approximately 1.40×10^{-6} at room temperature; the compressibility increases somewhat with rising temperature and decreases with metal of lower purity.

Thermal Expansivity—According to measurements of the Aluminum Research Laboratories,²⁸ the thermal expansivity of wrought aluminum (99.996% purity) is given by the following equation, for the temperature range of 20–500°C., L_0 is the original length and L_t the length at temperature t .

$$L = L_0 [1 + (23.22t + 0.00467t^2 + 0.0000078t^3) 10^{-6}]$$

The expansion coefficients for aluminum of different purities and for a variety of temperature ranges are given in Table II.

According to Henning,⁶ the expansion coefficient ($\alpha \times 10^{-6}$) of aluminum is 18.2 at –100°C. and 11.55 at –200°C. The following equation covers the range from 0 to –200°C.:

$$L_t = L_0 [1 + (22.65t + 0.01675t^2 - 0.00003667t^3) 10^{-6}]$$

Freezing Point—The Bureau of Standards issues a standard sample of very pure aluminum for melting point determinations, to which they assign a melting point of 660.2°C. Commercial metal having a purity of about 99.2% has a freezing point of about 657°C. (1214.6°F.).

Table II
Average Expansion Coefficients of Aluminum

Temp. Range, °C.	Average Coefficients of Expansion per °C.			
	Wrought Aluminum ²⁸ 99.996%	Cast Aluminum ⁵ 99.95%	Cast Aluminum ⁵ 99.74%	Rolled Aluminum ⁵ 99.15%
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
20–100	23.86	23.8	23.8	24.0
20–200	24.58	24.7	...	25.9
20–300	25.45	25.7	25.6	26.7
20–400	26.49	26.7	...	27.2
20–500	27.68	27.7	...	27.9
20–600		28.7	29.4	28.6
100–200		25.5		
200–300		27.5		
300–400		29.5		
400–500		31.5		
500–600		33.5		
300–600		31.5		

Specific Heat—The specific heat of aluminum as well as the heat content are given in Table III. Recent work of Seekamp²⁹ is in close agreement with the data of Table III.

Latent Heat of Fusion—The latent heat of fusion of aluminum is approximately 93 cal. per g. (167.4 B.t.u. per lb.), which is an average of the closely agreeing results of Wurst, Meuthen and Duerrert¹ and of Awbery and Griffiths.³

Boiling Point—The boiling point of aluminum is not known with great certainty but according to Greenwood⁹ it is 1800°C. (3272°F.). The metal is relatively non-volatile at ordinary melting and casting temperatures. Its vapor pressure is estimated by Johnston¹⁰ to be about 0.001 mm. of mercury at 730°C., 0.01 mm. at 830°C., and 0.1 mm. at 950°C. According to Johnston's estimate, the heat of vaporization is approximately 52,600 g. cal. per mol (27.0 g.) or 3506 B.t.u. per lb.

Table III
Heat Content and Specific Heat of Aluminum
Arranged by Shadgen⁷ from Data of Wuest, Meuthen, and Duerr

°C.	Temp. °F.	Heat Content		Specific Heat	
		B.t.u. per lb.	Calories per kg.	Mean 0°-T°	At T°
0	32	.....	.....	.....	0.2220
100	212	40.66	22.59	0.2259	0.2297
200	392	82.69	45.94	0.2297	0.2374
300	572	126.12	70.07	0.2336	0.2451
400	752	170.95	94.97	0.2374	0.2529
500	932	217.15	120.64	0.2413	0.2606
600	1,112	264.76	147.09	0.2452	0.2683
657 (Solid)	1,214.6	292.50	162.50	0.2473	0.2727
657 (Liquid)	1,214.6	461.63	256.45	0.3904	0.2502
700	1,292	481.09	267.27	0.3818	0.2523
800	1,472	526.93	292.74	0.3659	0.2571
900	1,652	573.66	318.70	0.3541	0.2619
1,000	1,832	621.26	345.14	0.3451	0.2667

Thermal Conductivity—The precise measurement of the thermal conductivity of metals is a difficult problem and it is not surprising that there is wide variation in the published data. The Bureau of Standards¹¹ reports that aluminum, 99.66% pure, has a thermal conductivity of 0.52 (cal. per sec. per sq. cm., per cm. of thickness per °C.) at an approximate temperature of 50°C. The thermal conductivity decreases with decrease in purity. Apparently it increases slightly with increase in temperature up to several hundred °C., but observers are not unanimous on this point. The average of scattered values of some 12 different investigators are as follows: 0.503 at room temperature; 0.503 at 100°C.; 0.530 at 200°C.; 0.546 at 400°C. A thermal conductivity of 0.52 in cgs. units is equivalent to 1509 B.t.u. per hr. per sq. ft. per in. of thickness per °F.

Heat of Combustion—The heat of combustion of aluminum with oxygen is high and accounts for the ready reduction of many oxides by reaction with aluminum. The average of the results of four investigations (Minet,¹² Berthelot,¹³ Richards,¹⁴ Parr and Moose¹⁵) is 383,900 cal. per mol of alumina formed ($2\text{Al} + 3\text{O} = \text{Al}_2\text{O}_3$), which is equivalent to 12,800 B.t.u. per lb. of aluminum.

Fluidity—The fluidity (reciprocal of viscosity) of aluminum according to the data of Losani¹⁶ is given in Table IV. The results are referred to the fluidity of tin at 300°C. as unity. The fluidity of aluminum is appreciably increased by the addition of small amounts of alloying elements.

Table IV
Fluidity Index of Aluminum
According to Losani

Temp., °C.	Fluidity Index— Fluidity of Pure Tin at 300°C. = 1.00	
	Aluminum Purity = 99.26%	Aluminum Purity = 98.32%
680	0.51	0.67
700	0.70	0.75
750	0.84	0.88
800	0.93	0.97
850	0.97	1.02
900	1.00	1.05
950	1.02	1.09
1,000	1.05	1.15

Optical Properties—Aluminum ranks high among metals as a reflector for ultra-violet light.¹⁷ In the visible range, reflectivity values as high as 90% have been recorded,¹⁸ while in the infra-red range the reflectivity increases to values of over 97%.¹⁹ Fig. 1, taken from an article by Edwards,¹⁹ shows the reflection factor for aluminum over a wide range of wave lengths; means of preparing aluminum reflectors are described in this article.

The emissivity of commercial aluminum foil is about 0.03 at room temperatures.²⁰

Moeller and Miething²⁰ found the emissivity of molten aluminum in contact with air to be 0.12 at 700°C. and 0.17 at 1000°C. The formation of an oxide film upon the metal had an appreciable effect upon the results and would tend to increase the observed emissivity.

Electrical Resistivity—Some of the electrical properties of annealed wire made from electrolytically refined aluminum with a purity of 99.996% are given in Table V. The resistivity is slightly increased by cold working.

Table V
Electrical Properties of High-Purity Annealed Aluminum Wire

Property	Value at 20°C.
Density	2.699 g. per cm. ³
Specific volume electrical resistivity, microhms per cm. cube.....	2.6548 × 10 ⁻⁶ ohms
Volume conductivity.....	64.94%
International annealed copper standard = 100	
Specific mass resistivity, ohms per m.g.....	0.07165 ohms
Mass conductivity.....	213.92%
International annealed copper standard = 100	
Constant mass temperature coefficient of resistivity.....	0.00429

The resistivity of liquid aluminum at its freezing point is 20 microhms per cc. according to Northrup,²¹ and 27 microhms per cc. according to Bornemann and Wagemann.²² The ratio of the resistivities of the liquid and solid at the melting point is about 1.64.

Aluminum Conductors—Commercial aluminum conductors are generally made from aluminum having a purity of about 99.5%. The American Institute of Electrical Engineers has adopted a tentative standard (No. 46) for the properties of hard drawn aluminum conductors, of which the principal parts are as follows:

1. **Resistivity**—At a temperature of 20°C. the electrical resistivity is 2.828 microhm-cm. (See Note 1.)
2. **Resistance Temperature Coefficient**—The 20°C. resistance temperature coefficient is 0.00403 per °C. (See Note 2.)
3. **Density**—At a temperature of 20°C. the density is 2.703 g. per cm.³
4. **Length Temperature Coefficient**—The 20°C. length temperature coefficient is 0.000023 per °C. (See Note 3.)
5. **Change in Resistivity with Change in Temperature**—The change in resistivity with change in temperature is 0.0115 microhm-cm. per °C. (See Note 4.)

Explanatory Notes

1. The values given above are consistent with resistivities at 20°C. of 17.01 ohm circular mil per ft. and 0.07644 ohm g. per sq. m., and a conductivity at 20°C., as compared with the annealed copper standard at 20°C. of 60.97%.

2. The value taken for the resistance temperature coefficient is the amount by which the resistance of a conductor of standard hard drawn aluminum changes when the temperature is changed, divided by the change in temperature expressed in °C., and divided by the resistance of the same conductor when at a temperature of 20°C.

3. The value taken for the length temperature coefficient (linear expansion coefficient) is the amount by which the length of a conductor of standard hard drawn aluminum changes when the temperature is changed, divided by the change in temperature expressed in °C., and divided by the length when at a temperature of 20°C.

4. The value taken for the change in resistivity with change in temperature, as given in paragraph 5, is the sum of the resistance temperature coefficient and the length temperature coefficient, multiplied by the resistivity at 20°C., as given in paragraphs 1, 2, and 4.

Electrochemical Equivalent—The electrochemical equivalent of aluminum is the number of g. deposited per sec. by a current of 1 ampere or the g. per coulomb. It is equal to the atomic weight, 26.97, divided by the valence, 3, and the constant 96,500, or 0.09316 mg. per coulomb. In various units it is as follows:

Electrochemical Equivalent of Aluminum

Unit	Value
Mg. per coulomb.....	0.09316
Coulombs per mg.....	10.734
G. per ampere hr.....	0.3354
Lb. per 1,000 ampere hr.....	0.7395
Ampere hr. per lb.....	1352.3

Electrolytic Solution Potential—According to standard terminology, aluminum is electronegative to the elements which it replaces in solution; the aluminum going into solution in the form of positive ions leaves the metal negatively charged, hence the characterization "electronegative." There is some question as to its exact position in the electrochemical series. In fact, its relative position appears to vary with the conditions under which it is tested, for example, the solute and solvent employed. Generally aluminum is considered to be electropositive to magnesium and electronegative to such metals as manganese, zinc, cadmium, iron, nickel, and copper. Under many practical conditions and probably because of film formation, zinc is found to be electronegative to aluminum.

Kahlenberg and French²⁸ have measured the potential of high purity aluminum (99.97%) in contact with aqueous normal solutions of potassium chloride. The potential was depressed when the solution contained dissolved oxygen, but when the oxygen was displaced with nitrogen, the pure aluminum showed an initial voltage against the normal calomel electrode of 1.716. In solutions in contact with air, the aluminum showed a potential of 0.8-1.0 volts. The single potential of the aluminum is 1.716 volts minus 0.56 (the potential of the calomel electrode) or 1.16 volts. According to Latimer and Greensfelder,²⁷ the electrode potential of aluminum at 25°C. has been calculated from thermal data to be 1.69 ± 0.01 volts.

Thermoelectromotive Force—The Bureau of Standards²¹ has determined the thermal emf. of electrolytically refined aluminum (99.968% purity) against pure platinum to be +0.416 millivolts at 100°C.; 1.064 at 200°C.; 1.884 at 300°C.; 2.843 at 400°C.; 3.931 at 500°C.; 5.150 at 600°C. The emf. corresponds to the temperatures of the hot junctions with the cold junctions at 0°C.; the plus sign indicates that the aluminum was at the higher potential. A sample of 99.972% purity had an emf. of 0.415 millivolts at 100°C.

Magnetic Properties—The purest aluminum is slightly but definitely paramagnetic. Apparently traces of iron in the aluminum, combined as FeAl₃, have only slight effect upon the magnetic properties of the metal. Honda²⁹ reports a value of $+0.65 \times 10^{-6}$ for the magnetic susceptibility (k) at 18°C., of aluminum with 0.08-0.24% iron and 0.695×10^{-6} for metal with an iron content of 0.80%.

Mechanical Properties—Aluminum of high purity is characterized by exceptional ductility and softness. A sample of 99.97% purity had the following mechanical properties in the wrought annealed condition:²

Tensile strength	8,500 psi.
Elongation	60% in 2 in.
Using the standard 0.5 in. dia. A.S.T.M. specimen	
Reduction in area.....	95%
Brinell number, with 50 kg. pressure and 0.125 in. ball.....	16

Aluminum of substantially lower purity, say 99.4% (annealed), will have about the following properties, which are interesting as a matter of comparison:

Tensile strength	13,000 psi.
Elongation	22
Reduction in area.....	80%
Brinell hardness	45 in 2 in.

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Properties of Commercially Pure Wrought Aluminum

By P. V. Faragher*

General—Commercially pure wrought aluminum (2S) contains small quantities of iron and silicon. It is available in practically all of the forms used in the metal industry. It possesses excellent workability and a high degree of resistance to corrosion and is generally used in applications requiring these properties rather than strength.

Composition—Specifications for commercially pure aluminum require a minimum of 99% aluminum.

Specific Gravity—The specific gravity of the metal is 2.71. One cu.in. weighs 0.098 lb.

Temper Designations—Temper of wrought aluminum is designated by a symbol or symbols following the alloy designation.

The suffix "O" designates annealed material while "H" indicates the full hard temper attained by cold working a definite amount after annealing. Cold worked tempers intermediate between the annealed and full hard are indicated by a fraction preceding the symbol "H," corresponding to the properties intermediate between annealed and hard rolled.

Mechanical Properties—Typical mechanical properties of commercially pure wrought aluminum in the various tempers are given in Table I.

Table I
Mechanical Properties¹ of Wrought Aluminum (2S)

Temper Designation (See Text)	Tensile Strength Psi.	Yield Strength ² Psi.	Elongation ³ , % in 2 in.	Brinell Hardness ⁴ No.	Shearing Strength ⁵ Psi.
O (Annealed)	13,000	5,000	35	23	9,500
1/4H	15,000	13,000	12	28	10,000
1/2H	17,000	14,000	9	32	11,000
3/4H	20,000	17,000	6	38	12,000
H (Hard)	24,000	21,000	5	44	13,000

¹Young's modulus of elasticity is approximately 10,300,000 psi. Rotating beam endurance limit (R. R. Moore type machine, 500,000,000 cycles) for 2S-O is 5,000 psi. and for H is 8,500 psi.

²Stress which produces a permanent set of 0.2% of the initial gage length. Yield strengths in tension and compression are substantially the same.

³Typical values for sheet 1/4-1/2 in. in thickness. Heavier sections, from which standard, round specimens are taken, will have higher elongations.

⁴10 mm. ball, 500 kg. load.

⁵Single shear strength values obtained from double shear tests.

Resistance to Corrosion—Commercially pure aluminum is highly resistant to the action of the atmosphere and a variety of chemicals. It is attacked by strong alkalis and to some extent by weak alkaline solutions. In the latter case the action may be inhibited by small additions of such compounds as sodium silicate or the chromates of sodium or potassium.

Workability—In its wrought forms the metal may be formed readily on the equipment commonly used for bending, spinning, drawing, and stamping metals. It is most workable in the annealed temper, although in the half hard temper it can be bent flat on itself. Less severe forming can be done in the harder tempers.

Welding Characteristics—Welding is easily accomplished with the oxyhydrogen or oxy-acetylene flame, the metal arc (except for thin sheets), and electric resistance processes. Some practice and experience is necessary for consistently reliable results, but the technique is not difficult to master. A welding rod of the same composition is used for work on the commercially pure metal and a suitable flux is necessary. Spot, butt, and seam welding are applicable but require more powerful equipment than is used on steel.

Annealing Treatment—The fully annealed properties are obtained by heating to 650°F. followed by air cooling.

*Aluminum Co. of America, Pittsburgh.

Applications and Forms Produced—The uses of commercially pure aluminum vary widely, but are typified in cooking utensils and chemical equipment. The metal is especially useful where a high degree of formability is necessary.

The metal is produced in the usual wrought forms such as sheet, plate, tubing, bar, rod, wire, rivets, molding, and other shapes.

Bars, rods, shapes, and plates over $\frac{1}{4}$ in. thick are normally hot rolled and their strength is somewhat above that of annealed material; no attempt is made to produce definite tempers. Cold finished bars and rods are harder and stronger. Plates are produced in tempers up to half hard, but when such properties are wanted it is usually more economical to use the as-rolled temper of a stronger alloy.

Properties of Aluminum-Copper Alloys

(General Article)

By E. H. Dix, Jr.,* and J. J. Bowman*

General—The aluminum-copper alloys as a class are probably the oldest and most widely used of any commercial aluminum alloys. The commercial alloys of aluminum and copper are, in general, not strictly binary alloys, but are modified by small amounts of other elements. The aluminum-copper alloy containing about 4% copper forms the base for some of the most important heat treatable, high strength aluminum alloys, both cast and wrought.

Casting Alloys

Casting Characteristics—The casting and general foundry characteristics of the commercial aluminum-copper alloys are very good. The addition of copper decreases, progressively, shrinkage difficulties and hot shortness, so that with 12% copper, leak-proof castings are readily produced. The 8% copper alloy is a good, general purpose alloy, but may give some trouble in casting if the iron and silicon contents are not properly controlled.

Mechanical Properties—The results of a limited investigation of sand cast, aluminum-copper alloys are shown by the curves of Fig. 1. As these curves show, the strength increases and the elongation decreases in direct proportion to the copper content. The most rapid changes in the properties are produced by copper additions of about 5% or less. The alloys containing more than about 10% copper are comparatively brittle, but are still of reasonable commercial value.

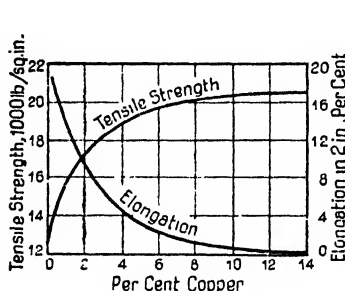


Fig. 1

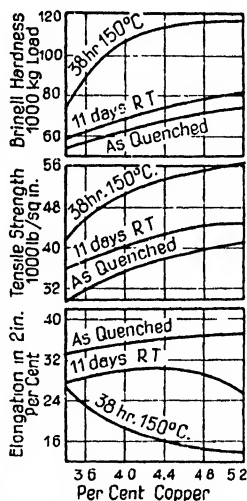


Fig. 2

Fig. 1—Tensile properties of aluminum-copper alloys in the form of $\frac{1}{2}$ in. dia. test bars cast in green sand.²

Fig. 2—Properties of high purity aluminum-copper alloys after hot rolling. Heating 1 hr., at 540°C., quenching in cold water, and aging as indicated (R.T. = room temperature).

increases with an increase in copper content, the upper limit for practical production of such alloys is probably 5-6% of copper. Such high purity alloys containing up to 5% copper can be hot rolled with relative ease and in the annealed condition have a greater capacity for cold work than the aluminum-copper alloys containing other added elements.

Mechanical Properties—Several investigations of the wrought high purity, aluminum-copper alloys have been made to determine the relations between copper content and mechanical properties. These studies indicate that, within reasonable

The mechanical properties of these binary alloys are subject to marked improvement by suitable heat treatments.¹ The commercial alloy most commonly used in the heat treated condition is that containing about 4% copper, because this composition will produce a suitable combination of strength and ductility in sand castings. The alloys of higher copper content, however, are frequently heat treated to increase hardness and toughness.

Wrought Alloys

Rolling Characteristics—Binary alloys of high purity containing up to 10% copper have been successfully rolled on a small scale, but since the difficulty of working in-

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¹U. S. Patents 1,394,534 and 1,572,487.

²The Aluminum Industry, v. II, p. 144. Fig. 2 from p. 147.

limits, the mechanical properties of annealed or hard rolled sheets are not greatly affected by variations in copper content from about 2.5-5% or somewhat higher.

The curves of Fig. 2 are a portion of the results of these investigations and illustrate clearly the effect of copper content on the mechanical properties of heat treated sheet. They illustrate the very definite increase in strength and hardness accompanying increased copper content and the unmistakable hardening (or precipitation) effect of room temperature aging. The further effect of aging at an elevated temperature is marked. The elongation in the "as-quenched" condition is quite high and is not greatly affected by variations in copper content. Similarly, there is not a great variation in elongation attributable to copper content in alloys aged 11 days at a room temperature. The definite maximum in this curve at from 4-4.5% copper should be noted.

Other Characteristics

Density—Both the solid and liquid densities of the aluminum-copper alloys, as would be expected, increase with the copper content. At 20°C. the density of the sand cast alloy containing 4% copper is about 2.77, while that of the 8% copper alloy is about 2.83. At 700°C. the values for these alloys become, respectively, about 2.44 and 2.53.

Thermal and Electrical Conductivity—In general, the thermal and electrical conductivities of aluminum are reduced by alloying additions, although the latter property is not as greatly affected in aluminum alloys as in the alloys of some of the other metals. Additions of copper to aluminum, in accordance with the general rule, decrease progressively both the thermal and electrical conductivities so that, with 8% copper present, the former becomes about 0.34 cgs. units and the latter is about 35% of the copper standard.

Thermal Expansion—The coefficients of thermal expansion of aluminum-copper alloys decrease continuously with increasing copper content from about 0.000024 per °C. (20-100°C.) for pure aluminum to about 0.000020 for the 33% copper alloy. The rate of decrease is greatest from 0 to about 8% copper.¹

Endurance Limit—The rotating beam endurance limit (500 million cycles) of the aluminum-copper alloys increases with increase in copper content and, for a given alloy, is improved by solution heat treatment.

Resistance to Corrosion—The addition of copper, in excess of the limit of solid solubility, tends to lower the high resistance to corrosion of pure aluminum, so that the resistance to corrosion of the aluminum-copper alloys is generally inferior to that of the aluminum-silicon, aluminum-manganese, and aluminum-magnesium alloys, but is satisfactory for most applications especially in relatively thick sections, as in castings. Thin sheets of the aluminum-copper alloys generally require protective measures to resist severely corrosive condition. Solution heat treatment definitely improves the resistance to corrosion, but subsequent precipitation heat treatments cause some reduction in this property, although the resulting product is definitely superior to the alloy in the unheat-treated condition.

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Properties of Aluminum-Copper (8%) Casting Alloys

By H. J. Rowe*

The aluminum casting industry in America has developed around alloys in which copper was the principal hardening constituent. Most important of this group of alloys still in general use are those in which approximately 8% copper is used as the chief alloying element. Later improvements in the simple binary alloy have led to the addition of controlled amounts of silicon, iron, and zinc, resulting in alloys with better casting characteristics and machinability. The chemical compositions and specifications for the aluminum-copper casting alloys in most general use are given in Table I, and the mechanical and physical properties in Table II.

Table I
Chemical Composition of 8% Copper Casting Alloys (Approx.)

Alloy	Copper %	Iron %	Silicon %	Zinc %	Aluminum (Min.) %
A	8.0	....	....	....	90.0
B	7.0	1.2	2.0	1.5	86.5
C	8.0	1.0	1.2	....	89.0
D	7.0	1.2	3.0	2.0	85.5
E	7.0	....	2.0	....	85.0

Aluminum-Copper (8%) Casting Alloys
Specifications

	Sand Castings			Permanent Mold Castings	Die Castings	Ingot
	A	B	C	D	E	B, C, D
Aluminum Co. of America.....	No. 12	No. 112	No. 212	No. C113	No. 81	.....
S.A.E.....	SAE 30	SAE 33	SAE 36	SAE 33	SAE 312	.....
A.S.T.M.....	.....	B26-3TT	B26-3TT	B108-3TT	B85-3TT	B58-3TT
		Alloy C	Alloy CC	Alloy 2	Alloy XII	B112-3TT
U. S. Army.....	57-72 Grade 5	57-72 Grade 7	11310	.....	.....	.....

General Properties and Uses—The aluminum-copper casting alloys containing 8% copper, although superseded in some fields of application by newer alloys with improved properties, still account for a large part of aluminum alloy casting production. They possess a desirable combination of general casting characteristics, good machinability, and fair mechanical properties, which warrant their use in a variety of fields.

Alloy A, the oldest of the group, is being replaced to a great extent by Alloys B, C, D and E because of their better casting characteristics and the better machinability as judged by surface appearance, offered by Alloys B and D. The composition limits for Alloys B and D are also such as to permit the use of various amounts of secondary material.

The corrosion resistance of this group of alloys, because of the high copper content, is not in general so good as that of many of the low copper alloys, such as aluminum-silicon, and aluminum-magnesium alloys.

One of the first uses for castings of the 8% copper alloys was in the automotive industry, where the mechanical properties were quite satisfactory for such parts as crankcases, oil pans, transmission housings, manifolds, and miscellaneous fittings for bodies, chassis and engine. Many parts for washing machines, vacuum cleaners, multigraphs, typewriters, and other machines, not subject to extreme stresses and impact, are produced in these alloys. It is estimated that 50% of the aluminum foundry output of castings is made in 8% copper alloys.

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Table II
Physical Properties of Aluminum-Copper (8%) Casting Alloys

	A	Sand Cast B	C	Permanent Mold Cast D	Die Cast E
Ultimate tensile strength, psi. (min. to average) ¹	19,000-22,000	19,000-23,000	19,000-23,000	25,000-28,000	27,000-32,000
Yield strength, psi. (average) ²	14,000	14,000	14,000	24,000	24,000
Elongation, % in 2 in. (min. to average).....	0-2.0	0-1.5	0-2.0	0-0.5	0-1.5
Brinell hardness, 10 mm. ball, 500 kg. load.....	50-70	55-80	50-70	70-90	70-90
Rockwell hardness, 1/8 in. ball, 100 kg. load.....	E80-E80	E85-E87	E80-E80	E80-E91	E80-E91
Yield strength in compression, psi. (approx.) ³	14,000	17,000	16,000	24,000	.....
Ultimate compressive strength, psi. (approx.) ³	64,000	62,000	57,000	71,000	.....
Shearing strength, psi. (ap- prox.) ⁴	20,000	20,000	20,000	22,000	.....
Charpy impact resistance, ft.- lb. (approx.) ⁵	0.7	0.6	0.6	.....	3.0
Endurance limit, psi. (approx.) ⁶	7,500	8,500	7,500	.....	16,000
Modulus of elasticity, psi. (ap- prox.).....	10,300,000	10,300,000	10,300,000	10,300,000	10,300,000
Specific gravity (approx.).....	2.83	2.85	2.83	2.86	2.85
Weight per cu. in., lb. (approx.)	0.102	0.103	0.102	0.103	0.103
Pattern maker's shrinkage, in. per ft.....	5/32	5/32	5/32	.....	.....
Solidification range—°F.....	1175-1005	1175-1005	1165-975	1165-975	1165-975
Electrical conductivity, % of copper standard at 68°F. (approx.) ⁷	37	30	30	27	28
Thermal conductivity at 25°C., cgs. units (approx.) ⁷	0.35	0.29	0.29	0.26	0.27
Coefficient of thermal expansion, °F. (68-212°F.) (ap- prox.).....	0.0000125	0.0000122	0.0000122	0.0000122	0.0000123

¹Tension and hardness values for sand and permanent mold castings determined from standard one-half inch diameter specimens separately cast in green sand and metal molds respectively. Tension and hardness values for die castings determined from standard one-quarter inch diameter die cast specimens. All specimens tested without machining of gage length.

²Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.

³Results of tests on specimens having an l/r ratio of 12. Specimens failed in shear.

⁴Single shear strength values from double shear tests.

⁵Charpy impact values as determined using 10 x 10 mm. specimens on modified Charpy machine with 5.07 lb. hammer. Sand and permanent mold specimens notched. Die cast specimens not notched.

⁶Endurance limit based on 500,000,000 cycles using R. R. Moore type rotating beam machine. Sand and permanent mold specimens machined from tension specimens. Die cast specimens cast to size and tested without machining of gage section.

⁷Based on specimens machined from bars individually cast in chill molds and free from porosity and internal defects.

Properties of Heat Treated Aluminum-Copper (4%) Casting Alloys

By H. J. Rowe*

Certain of the aluminum alloys derive exceptional mechanical properties from heat treatment operations. The 4% copper alloy with controlled amounts of silicon and iron† is the most generally known of these high strength casting alloys. By varying the heat treatment of this alloy, several combinations of mechanical properties may be obtained to fit particular engineering requirements.

The properties of the 4% copper alloy with a minimum of 93% aluminum in three standard heat treated conditions are as follows:

Physical Properties of Heat Treated Copper Casting Alloy (4% Cu)

	Heat Treatments		
	A	B	C
Ultimate tensile strength, psi. (min. to average ¹).....	29,000-31,000	32,000-36,000	36,000-40,000
Yield strength, psi. (average ²).....	16,000	22,000	31,000
Elongation in 2 in., % (min. to average).....	6.0-8.5	3.0-5.0	0.0-2.0
Brinell hardness, 10 mm. ball, 500 kg. load.....	55-75	70-90	80-100
Rockwell hardness, 1/4 in. ball, 100 kg. load.....	E66-E84	E80-E93	E87-E98
Yield strength in compression, psi. (approx. ^{3, 4}).....	16,000	25,000	38,000
Shearing strength, psi. (approx. ⁴).....	24,000	30,000	31,000
Charpy impact resistance, ft.-lb. (approx. ⁵).....	3	2	1
Endurance limit, psi. (approx. ⁶).....	6,000	6,500	7,000
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000	10,300,000
Specific gravity (approx.).....	2.77	2.77	2.77
Weight per cu. in., lb. (approx.).....	0.100	0.100	0.100
Pattern maker's shrinkage, in. per ft.	3/32	3/32	3/32
Solidification range, °F.....	1195-1020	1195-1020	1195-1020
Electrical conductivity, % of copper standard at 68°F. (approx. ⁷).....	35	.....	37
Thermal conductivity at 25°C., cgs.....	0.33	.....	0.34
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.).....	0.0000127	0.0000127	0.0000127

Note: The footnotes for this tabulation are the same as those given in the article "Properties of Aluminum-Copper Casting Alloy, Containing 8% Copper."

Specifications (Sand Castings)

	Heat Treatments			Ingot
	A	B	C	
Aluminum Co. of America.....	No. 195-T4	No. 195-T6	No. 195-T62	No. 195
Society of Automotive Engineers....	No. 38	No. 38	No. 38	.....
American Society for Testing Materials	{B-26-37T Alloy G Heat Treat. No. 1	{B-26-37T Alloy G Heat Treat. No. 2	{B-26-37T Alloy G Heat Treat. No. 3	{B-85-31 Alloy G
Federal Specifications.....	QQ-A-601 Class 4	QQ-A-601 Class 4	QQ-A-601 Class 4	QQ-A-371 Class 4
U. S. Army.....	57-72-5A	57-72-5B	.....	.....
U. S. Navy.....	46A1c Class 4	.....	.....	46A5c Class 4

General Properties and Uses—The casting characteristics of this 4% copper alloy are not quite so good as those of the 8% copper alloys. However, with proper foundry technique, large and intricate castings can be cast and heat treated successfully. In any of the heat treated conditions the 4% copper alloy machines very readily to a smooth surface. It also exhibits good corrosion resistance, particularly in the "A" heat treated condition. The corrosion resistance in the "B" and "C" condition is slightly inferior to that of the "A."

The 4% copper alloy with heat treatment "A," a solution treatment followed only by a quench, possesses the highest ductility and impact resistance, and is to be recommended where maximum shock resisting properties combined with high strength are required. The yield strength of the solution treated alloy increases

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†U. S. Patent No. 1,572,487.

substantially during the first few days at room temperature, then more slowly for a period of a few months, after which there is no further appreciable change. During this period, some increase in tensile strength and decrease in elongation also takes place. The mechanical properties given in the above table are representative of specimens tested with not less than two days or more than four days of room temperature aging.

Heat treatment "B," consisting of a solution treatment followed by a partial precipitation treatment, results in a material increase in yield strength, tensile strength, hardness, and a reduction of elongation to a point still consistent with engineering requirements. For general engineering purposes this treatment has found wide favor because of the excellent combination of mechanical properties which result.

Heat treatment "C" carries the precipitation treatment following the solution treatment to such a length as to produce the maximum hardness, yield strength, and tensile strength combination consistent with the avoidance of excessive brittleness. This treatment is desired where maximum yield strength is necessary and the castings are not subjected to excessive impact conditions.

The heat treated 4% copper alloy finds numerous applications in cast parts for aircraft engines and fuselage fittings, outboard motor parts, automotive and marine castings, Diesel engine crankcases, and railway car fittings. The choice of heat treatment will depend upon operating conditions and mechanical properties desired. For the more intricate castings, those requiring pressure tightness, and those subjected to extreme corrosive conditions, this alloy is being replaced to some extent by the more recently developed heat treated aluminum-silicon-magnesium alloys.¹

A nominal 4% copper alloy with a minimum aluminum content of 94.5%² has also found some commercial use because of the higher mechanical properties after heat treatment. This alloy is, however, very difficult to cast and cannot be used successfully for intricate castings.

The 4% copper alloy with slight variations in composition to insure the necessary casting characteristics, may also be used in the production of permanent mold castings. In the heat treated condition such permanent mold castings will exhibit considerably higher mechanical properties than those given for sand castings.

¹R. S. Archer and L. W. Kempf, Aluminum-Silicon-Magnesium Casting Alloys, Inst. Metals Div., A.I.M.E., 1931, v. 83, p. 448.

²R. S. Archer and Zay Jeffries, Aluminum Castings of High Strength, Inst. of Metals Div., A.I.M.E., 1927, v. 75a, p. 35.

Properties of Aluminum-Magnesium Alloys

By L. W. Kempf* and F. Keller†

The binary alloys of aluminum with magnesium attracted the interest of investigators as early as the year 1900, and there have been numerous attempts to utilize for general purposes alloys containing up to 10% magnesium. Alloys containing as high as 30% magnesium have been used for special purposes.

The aluminum-magnesium alloys are lighter than aluminum, have good physical properties, excellent resistance to corrosion and are easily machined. The relatively high cost of magnesium and certain fabricating difficulties sufficed to retard their commercial exploitation. The price of magnesium has been considerably reduced and some success has been attained in overcoming some of the fabricating difficulties.

Contemporaneous efforts are being made both in this country and abroad to exploit commercially some of the aluminum-magnesium type alloys. In this country there has been some production in the form of castings of alloys containing about 4% and about 10% magnesium. Wrought alloys containing from about 1-6% magnesium as the principal alloying ingredient are also being introduced to the trade. Abroad a casting alloy containing 2-3% magnesium with additions of manganese and antimony is being produced. Wrought alloys containing 5-9% magnesium are being marketed abroad principally in the form of sheet.

Density—The densities of solid aluminum-magnesium alloys decrease continuously with magnesium content as indicated by the curve of Fig. 1.

Thermal Expansivity—The coefficient of thermal expansion of magnesium is somewhat higher than that of aluminum and the expansivity of aluminum-magnesium alloys increases with magnesium content according to Fig. 2.

Growth—The precipitation of magnesium constituent from a supersaturated aluminum solid solution is accompanied by a slight decrease in density. An alloy containing 10% magnesium in solid solution showed, upon heating to the neighborhood of 400°F. for a sufficient period of time to bring about complete stabilization, a change in density corresponding to a unit linear expansion of 0.0015.

Electrical and Thermal Conductivity—The electrical conductivity of aluminum decreases continuously with increasing magnesium content as shown by Fig. 3. Determinations on which this curve was based were made on alloys quenched from a high temperature solution treatment. Alloys so treated as to contain a minimum amount of magnesium in solid solution would ordinarily have appreciably higher electrical conductivities than are indicated by this curve.

A knowledge of the general relationship between electrical and thermal conductivity of aluminum alloys permits the estimation of thermal conductivity from electrical conductivity as indicated in Fig. 3.

Casting Characteristics—Alloys containing up to about 5% magnesium may be cast in ordinary green sand molds. When so cast, especially in heavy sections, alloys with magnesium concentrations higher than this develop a dark, porous outer ring. This effect is commonly referred to as burning and appears to consist largely of intergranular cavities, presumably caused by shrinkage and reaction of the aluminum-magnesium intermetallic compound with moisture or the atmosphere. The alloys tend to dross badly when molten, which tendency increases with magnesium content. These difficulties have been overcome successfully in a commercial way by the development of foundry technique. Inherently the aluminum-magnesium alloys are not especially difficult to cast, being quite fluid and not especially hot short, very little difficulty having been encountered from cracking in the relatively large castings. Pressure tight castings are not as easily obtained with the aluminum-magnesium as with the aluminum-silicon alloys.

Tensile Properties and Hardness of Sand Castings—The variation in mechanical properties of sand cast aluminum-magnesium alloys with magnesium content is shown in Fig. 4.

The variation in solid solubility of magnesium in aluminum from about 15% at the eutectic temperature of 451°C. to less than 4% at room temperature renders

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†Aluminum Research Laboratories, Aluminum Co. of America, New Kensington, Pa.

some of the alloys susceptible to improvement in properties by heat treatment. The curves of Fig. 5 show the variation in properties of heat treated sand castings with magnesium content. These properties were attained by subjecting the castings to a solution heat treatment near the eutectic temperature for a sufficient period of time to bring about substantially complete solution of the magnesium constituent or saturation of the aluminum solid solution. The castings were quenched in water from the solution heat treatment. A comparison of the curves of Fig. 4 with those of Fig. 5 indicates that heat treatment brings about a profound change in the properties of alloys containing more than 6% magnesium. These properties were determined on $\frac{1}{4}$ in. dia. test bars cast in green sand of alloys whose impurity contents were carefully controlled, the iron and silicon contents being not more than 0.25% and copper rarely higher than 0.15%.

Working Characteristics—Alloys containing up to 2 or 3% magnesium can be reduced from cast ingots by forging or rolling with little difficulty. With increasing magnesium contents above about 3%, breaking down cast ingots becomes increasingly difficult. Even at the optimum hot working temperature, the alloys appear quite hard and are subject to considerable breakage, edge cracking, and surface checking. These conditions have precluded the commercial development and application of wrought alloys containing more than about 6% magnesium in spite of the fact that sheet and other wrought products containing up to 10% magnesium may be produced in limited sizes and at an excessive cost. The alloys may be extruded with magnesium concentrations as high as 25%. Extrusion rates decrease rapidly with increase in magnesium content.

Properties of Wrought Alloys—Fig. 6 shows the change in tensile properties and hardness of aluminum-magnesium alloys with variation in the magnesium content. Up to about 10% magnesium the data from which Fig. 6 was derived were obtained from forged bars. Above 10% magnesium the material from which the test bars were taken was produced by extrusion. The test specimens were heated near the eutectic temperature for a sufficient period of time to bring about substantially complete solution of the intermetallic constituent or saturation of the aluminum solid solution and then quenched in water. The alloys were of high purity, containing not more than about 0.1% each of iron, silicon, and copper. It will be noted that tensile strength increases to a maximum at about 15% magnesium which approximates the maximum solubility of magnesium in solid aluminum. As the magnesium content increases above this concentration, the tensile strength falls quite rapidly. Brinell hardness and yield strength increase continuously with magnesium content. A relatively constant elongation of about 32% from 2-12% magnesium is noteworthy.

Fig. 7 shows the mechanical properties obtained on a series of specimens of sheet alloys containing from 1-10% magnesium. Fig. 8 shows the properties of the same series of alloys after a reduction in thickness of 75% by cold working.

Impact Resistance—The impact resistance of aluminum as measured by notched bar Charpy or Izod tests increases with magnesium content up to at least 6% magnesium, the Izod impact resistance of the 6% alloy being about 38 ft-lb. as compared with about 21 ft-lb. for annealed commercially pure aluminum and about 16 ft-lb. for commercial duralumin. The heat treated sand cast alloy containing 10% magnesium has a Charpy impact resistance of about 4.5 ft-lb. as compared with 2.8 ft-lb. for the commercial heat treated 4% copper casting alloy.

Fatigue Resistance—The endurance limit based on 500,000,000 reversals of stress of wrought aluminum is increased with magnesium content from about 5,000 psi. at 0 magnesium to about 20,000 psi. at 6% magnesium. With higher magnesium concentrations the rate of increase is much slower, the 10% magnesium alloy having an endurance limit of about 21,000 psi. The effect of increasing concentrations of magnesium on the endurance limit of aluminum is shown in Fig. 9. The aluminum-magnesium alloys have a higher ratio of endurance limit to tensile strength than the aluminum-silicon, aluminum-copper, or aluminum-zinc alloys.

Properties at Elevated Temperatures—As indicated in Fig. 10 and 11 for sand castings of a 4 and a 10% magnesium alloy respectively, tensile properties of these alloys at elevated temperatures are relatively higher than those of alloys of the aluminum-silicon or aluminum-zinc systems but generally not as high as the corresponding aluminum-copper alloys. The data on which these curves are based

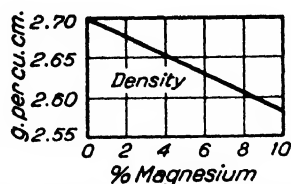


Fig. 1—Density of aluminum-magnesium alloys at 70°F.

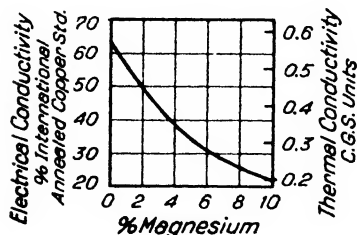


Fig. 3—Electrical and thermal conductivities of aluminum-magnesium alloys.

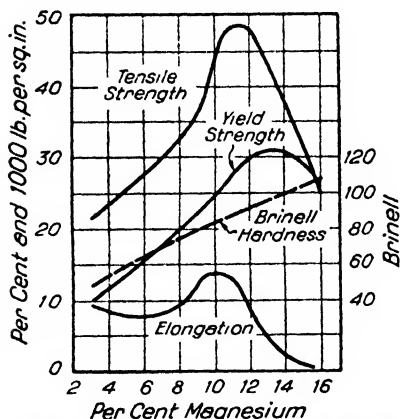


Fig. 5—Tensile properties and hardness of heat treated sand cast aluminum-magnesium alloys.

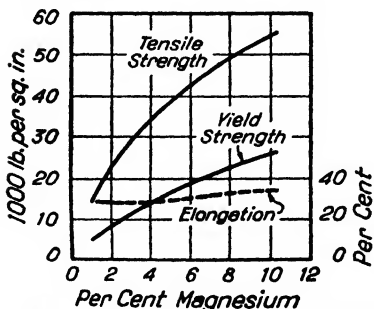


Fig. 7—Tensile properties of aluminum-magnesium alloy sheet in the heat treated condition.

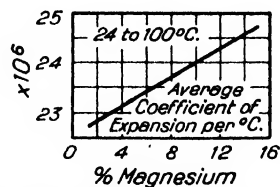


Fig. 2—Thermal expansivity of aluminum-magnesium alloys.

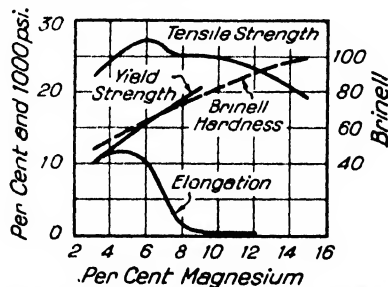


Fig. 4—Tensile properties and hardness of cast aluminum-magnesium alloys in the "as cast" condition; $\frac{1}{2}$ in. dia. test bars cast to size in green sand

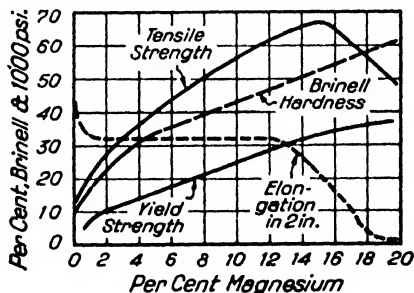


Fig. 6—Tensile properties and hardness of forged or extruded aluminum-magnesium alloys in the heat treated condition.

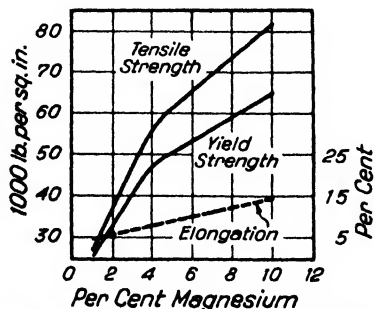


Fig. 8—Tensile properties of aluminum-magnesium alloy sheet, cold rolled 75% after heat treatment.

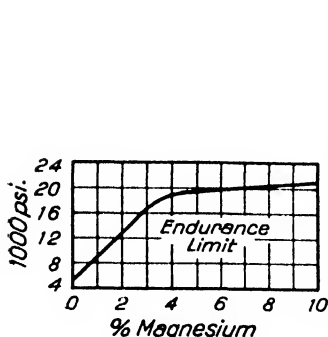


Fig. 9—Endurance limits of wrought aluminum-magnesium alloys.

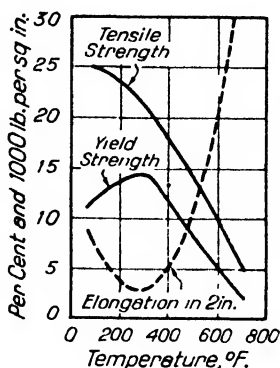


Fig. 10—Tensile properties of 4% magnesium alloy sand cast test bars at elevated temperatures.

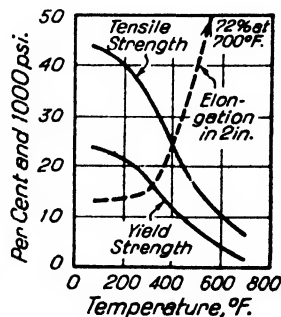


Fig. 11—Tensile properties of 10% magnesium alloy sand cast test bars at elevated temperatures.

were determined on test bars cast to size in green sand and heated at the temperature of testing for such periods of time as required to bring about complete stabilization.

Resistance to Corrosion—The resistance of the cast aluminum-magnesium alloys to atmospheric and salt spray corrosion is excellent, being of a different order of magnitude than that of casting alloys of the aluminum-silicon, aluminum-copper, or aluminum-zinc systems. The aluminum-magnesium alloys generally preserve a better appearance and suffer less loss in mechanical properties than the more common casting alloys. As in most aluminum alloys, the presence of impurities has a marked adverse effect on resistance to corrosion.

The wrought alloys also in the compositions being produced commercially in this country have excellent resistance to corrosion.

The aluminum-magnesium alloys are also the most resistant to alkaline corrosion of any of the aluminum alloys. Resistance to this type of corrosion increases with magnesium content.

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Properties of Heat Treated Aluminum-Magnesium (10%) Casting Alloy

By L. W. Kempf* and H. J. Rowe†

The binary aluminum alloy containing 10% magnesium has the lowest specific gravity and is capable of developing the highest tensile strength of any of the aluminum casting alloys in commercial use at present. The mechanical properties after a high temperature solution treatment and some of the physical properties of this alloy are given in the following table:

Physical Properties of Heat Treated 10% Magnesium Casting Alloy

Ultimate tensile strength, psi. (Min. to average) ¹	42,000-45,000
Yield strength, psi. (average) ²	25,000
Elongation, % in 2 in. (min. to average).....	12.0-14.0
Brinell hardness, 10 mm. ball—500 kg. load.....	70-85
Rockwell hardness, ½ in. ball—100 kg. load.....	E81-E90
Yield strength in compression, psi. (approx.) ^{3,4}	26,000
Shearing strength, psi. (approx.) ⁴	33,000
Charpy impact resistance, ft.-lb. (approx.) ⁵	4.50
Endurance limit, psi. (approx.) ⁶	7,000
Modulus of elasticity, psi. (approx.).....	10,300,000
Specific gravity (approx.).....	2.55
Weight per cu.in., lb. (approx.).....	0.092
Pattern maker's shrinkage, in per ft.....	⅛
Solidification range, °F. (approx.).....	1150-840
Coefficient of thermal expansion per °F. (68-212°F.) (approx.).....	0.0000136
Electrical conductivity, % of copper standard at 68°F. (approx.).....	21
Thermal conductivity at 25°C., cgs. units (approx.).....	0.20

¹Tension values determined from ½ in. dia. specimens, separately cast in green sand molds and tested without machining off the surface.

²Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.

³Results of tests on specimens having l/r ratio of 12.

⁴Single shear strength values from double shear tests.

⁵Charpy impact values as determined using 10 x 10 mm. specimens on modified Charpy machine with 5.07 lb. hammer.

⁶Endurance limit based on 500,000,000 cycles using R. R. Moore type rotating beam machine.

Specifications

Source	Sand Castings
Aluminum Co. of America.....	No. 220-T4
U. S. Army.....	No. 11309A
U. S. Navy.....	No. M186b
Society of Automotive Engineers.....	SAE 324

General Properties and Uses—The casting characteristics of the 10% magnesium alloy are slightly inferior to those of the 4% copper alloys. The high magnesium concentration necessitates a special foundry technique to avoid oxidation of the surface of metal with the consequent darkening of the casting and loss in mechanical properties. This alloy is not generally recommended for castings which must be leak proof.

In addition to the superior mechanical properties, the excellent corrosion resistance and low specific gravity of the 10% magnesium alloy are worthy of note. The alloy machines with less tool wear but with longer chips to as smooth a finish as the 8% copper casting alloy.

The principal uses of the heat treated 10% magnesium alloy to date have been in railroad car construction. Such castings as truck frames, electric motor housings, car body fittings, bolsters, and draft gear parts have been satisfactorily produced. In addition, this alloy is recommended for clamshell and drag line bucket fittings, miscellaneous automotive castings, and all general castings requiring maximum strength and impact resistance.

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†Technical Department, Castings Division, Aluminum Co. of America, Cleveland.

Properties of Aluminum-Magnesium (4%) Casting Alloy

By L. W. Kempf* and H. J. Rowet†

This alloy is characterized by its low specific gravity, excellent mechanical properties, machinability and corrosion resistance, and ability to take and hold a high white polish. The casting characteristics are not so good as those of the aluminum-silicon alloys, especially in intricate castings. The mechanical and physical properties are listed in the following table:

Physical Properties of 4% Magnesium Casting Alloy

Ultimate tensile strength, psi. (min. to average) ¹	22,000-25,000
Yield strength, psi. (average) ²	12,000
Elongation, % in 2 in. (min. to average).....	6.0-9.0
Brinell hardness, 10 mm. ball—500 kg. load.....	40-60
Rockwell hardness, ½ in. ball—500 kg. load.....	E34-E72
Yield strength in compression, psi. (approx.) ^{2,3}	12,000
Shearing strength, psi. (approx.) ⁴	20,000
Charpy impact resistance, ft.-lb. (approx.) ⁵	3.80
Endurance limit, psi. (approx.) ⁶	5,500
Modulus of elasticity, psi. (approx.).....	10,300,000
Specific gravity (approx.).....	2.64
Weight per cu. in., lb. (approx.).....	0.095
Pattern maker's shrinkage, in. per ft.	⅓
Solidification range—°F., (approx.).....	1185-1075
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.).....	0.000133
Electrical conductivity, % copper standard at 68°F. (approx.).....	35
Thermal conductivity at 25°C., cgs. units (approx.).....	0.32

¹Tension values determined from ½ in. dia. specimens, separately cast in green sand molds and tested without machining off the surface.

²Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.

³Results of tests on specimens having 1/r ratio of 12.

⁴Single shear strength values from double shear tests.

⁵Charpy impact values as determined using 10 x 10 mm. specimens on modified Charpy machine with 5 07 lb. hammer.

⁶Endurance limit based on 500,000,000 cycles using R. R. Moore type rotating beam machine.

Specifications (Sand Castings)

Source	Alloy	Ingot
Aluminum Co. of America.....	No. 214	No. 214
U. S. Army.....	No 57-72-4	46 A5c Class 5
U. S. Navy.....	46 A1c Class 5	.....
Society of Automotive Engineers.....	S.A.E. 320	.....
American Society for Testing Materials.....	B26-37T Alloy L	B58-37T Alloy L

General Properties and Uses—As mentioned above, the casting characteristics of the 4% magnesium alloy are somewhat inferior to those of the aluminum-silicon alloys. Although it handles satisfactorily in castings of uniform section, it is somewhat difficult to cast in heavy intricate shapes, especially if pressure tightness is required. These limitations can in most cases be overcome, however, through modified foundry practice.

The excellent combination of mechanical and physical properties exhibited by the 4% magnesium alloy, particularly corrosion and tarnish resistance, makes this alloy very desirable for use in sanitary dairy equipment, cooking utensils, pipe fittings, carburetor cases and small ornamental castings requiring a high white polish. The alloy machines to a smooth surface with a relatively low rate of tool wear which adds materially to its utility for small mechanical fittings and housings.

For use with permanent molds, the composition of this alloy is modified slightly to give the desired casting characteristics.

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†Technical Department, Castings Division, Aluminum Co. of America, Cleveland.

Properties of Wrought Aluminum-Manganese Alloy

By P. V. Faragher*

General—Wrought aluminum-manganese alloy (3S) is similar to commercially pure aluminum, but it has higher hardness and strength with concurrent reduction in workability. It is available in the annealed, intermediate, and full hard tempers and in the usual forms and shapes.

Composition—The following comprises a commercial specification. Also the alloy contains small amounts of iron and silicon as found in commercially pure aluminum.

Manganese	1.0- 1.5%
Copper (max.)	0.2%
Aluminum (min.)	97.0%

Specific Gravity—The specific gravity of this alloy is 2.73. One cu.in. weighs 0.099 lb.

Temper Designations—The temper of wrought aluminum alloys is designated by a symbol or symbols following the alloy designation as explained in the article entitled "Commercially Pure Wrought Aluminum."

Mechanical Properties—Typical mechanical properties of the several tempers are given in Table I.

Corrosion Resistance—The corrosion resistance of the aluminum-manganese alloy approximates that of commercially pure aluminum. This alloy frequently replaces the pure metal when somewhat greater strength is desired.

Workability—The workability of this alloy in the annealed temper (O) almost equals that of commercially pure aluminum, though for very deep drawing or severe spinning operations the latter usually is specified. In tempers up to half hard ($\frac{1}{2}$ H), the alloy is extensively used for drawn cooking utensils. In the thin gages, these tempers will take a 180° flat bend. A more liberal bend radius is necessary in the three-quarter hard temper ($\frac{3}{4}$ H), while in the hard temper (H) little forming is possible.

Welding Characteristics—The aluminum-manganese alloy is welded readily with the oxy-hydrogen or oxy-acetylene flames, the metal arc (except for thin sheets), and the common resistance welding processes. A commercially pure aluminum welding rod is used and a suitable flux must be employed. The required technique is the same as for welding commercially pure metal.

Table I
Mechanical Properties¹ of Wrought Aluminum-Manganese Alloys (3S)

Temper Designation	Tensile Strength ² Psi.	Yield Strength ³ Psi.	Elongation ⁴ , % in 2 in.	Brinell Hardness ⁵ No.	Shearing Strength ⁶ Psi.
O (Annealed)	16,000	5,000	30	28	11,000
$\frac{1}{4}$ H	18,000	15,000	10	35	12,000
$\frac{1}{2}$ H	21,000	18,000	8	40	14,000
$\frac{3}{4}$ H	25,000	21,000	5	47	15,000
H (Hard)	29,000	25,000	4	55	16,000

¹Young's modulus is approximately 10,300,000 psi. Rotating beam endurance limit (R. R. Moore type machine, 500,000,000 cycles) for 3S-O is 6,000 psi., for $\frac{1}{4}$ H is 9,000 psi. and for H is 10,000 psi.

²Stress which produces a permanent set of 0.2%. Yield strengths in tension and compression are substantially equal.

³Typical values for sheet $\frac{1}{8}$ - $\frac{1}{2}$ in. in thickness. Heavier sections, from which standard, round specimens are taken, will have higher elongations.

⁴10 mm. ball, 500 kg. load.

⁵Single shear values from double shear tests.

Annealing Practice—The fully annealed properties are obtained by heating to 775°F. for about 2 hr. and cooling in the air.

Applications and Forms—This alloy is used for architectural applications such as roofing, flashing, gutters, and doors and is used in the construction of railway cars and other vehicles for parts which are not highly stressed or forming operations not too severe. This alloy is used in the manufacture of furniture, cooking utensils, and chemical equipment. Like the commercially pure metal (2S), it is produced in the common forms such as sheet, plate, tubing, bar, rod, wire, rivets, molding, and other shapes.

*Aluminum Co. of America, Pittsburgh.

Properties of Aluminum-Silicon Alloys

By L. W. Kempf*

General—Silicon probably stands second to copper in importance as an ingredient in aluminum casting alloys. Attention was directed to the many advantageous properties of these alloys by the discovery in 1921 by A. Pacz¹ of a method of modifying their structure and thus improving their tensile properties by treating the molten alloy immediately before casting with small amounts of sodium fluoride.^{2,3} Probably the most generally valuable property of the aluminum-silicon alloys is their excellent casting qualities, including superior fluidity and freedom from hot shortness. The strength and hardness obtained on the binary alloys are not at all remarkable. Other advantages of the silicon alloys are high resistance to corrosion, low specific gravity, low thermal expansion and high conductivity for heat and electricity. The chief use of the binary alloys is in castings containing about 5-13% silicon.

Density of Solid Alloys—Edwards⁴ has determined the density of alloys containing up to about 18% silicon. The diagram in Fig. 1 presents his data. These numerical values are approximately equal to the specific gravity. The complete density curves of alloys containing 3 concentrations of silicon are given in Fig. 2.

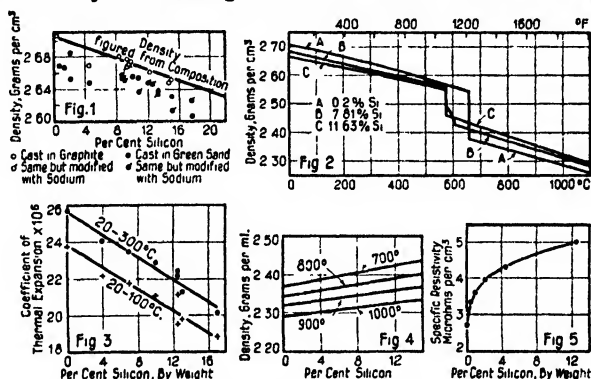


Fig. 1—Density of aluminum-silicon alloys.
Fig. 2—Density of alloys containing 3 concentrations of Si.
Fig. 3—Coefficient of expansion of Al-Si alloys.
Fig. 4—Density of liquid Al-Si alloys.
Fig. 5—Electrical resistivity of Al-Si alloys.

Thermal Expansivity—The coefficient of thermal expansion of silicon is less than $\frac{1}{2}$ that of aluminum and the aluminum-silicon alloys have appreciably lower expansivity than pure aluminum. The variation in coefficient of expansion with silicon content is indicated in Fig. 3.

Growth—The solubility of silicon in solid aluminum varies with temperature from about 0.05% at 200°C. (390°F.) to 1.65% at 577°C. (1070°F.). Alloys quenched from a high temperature solution treatment are of appreciably higher density than the same alloys in equilibrium at room temperature. The magnitude of this difference in density is small under all conditions but is greater the higher the degree of supersaturation. Thus with ordinary sand castings the rate of cooling is such that for all practical purposes, and especially for uses involving temperatures under 200°F., no changes can be detected. Changes in density have been estimated by measuring the linear change in dimensions accompanying reheating to elevated temperatures of alloys quenched from high temperature solution treatments. This change in dimension has been termed "growth" or "permanent growth." The maximum amount of growth observed in alloys containing more than about 1.7% silicon quenched from near the eutectic temperature corresponds to a unit change in lineal dimensions of 0.0016. Heating for 10-20 hrs. at 400-450°F. is required to bring about equilibrium as regards growth. The time for attainment of equilibrium varies inversely with temperature in a logarithmic manner.

*Aluminum Research Laboratories, Aluminum Co. of America, Cleveland.

Density of Liquid Alloys—The density of liquid aluminum-silicon alloys as determined by Edwards is given in Fig. 4.

Solidification Shrinkage—The percentage change in volume from a liquid at the melting point to a solid at the freezing point is known as solidification shrinkage. Edwards gives the solidification shrinkage of pure aluminum as 6.6%, that of an alloy of 7.81% silicon as 5.6%, and of an alloy of 11.63% silicon as 3.8%. The change in solidification shrinkage with silicon content is illustrated in Fig. 2.

Pattern Shrinkage—The pattern shrinkage is usually determined by casting a straight cylindrical bar between a pair of graphite or metal plates rigidly maintained a known distance apart and measuring the length of the bar when cold. Determinations by Edwards on alloys containing 12.55% and 22.4% silicon give a shrinkage of 0.16 and 0.15 in. per ft. respectively. The usual pattern shrinkage used in aluminum foundries for all aluminum alloys is $\frac{1}{32}$ in. (0.156 in.) per ft.

Electrical Resistivity—Increasing amounts of silicon increase the electrical resistivity of aluminum-silicon alloys as indicated in Fig. 5. These data are from measurements by J. D. Edwards on sand cast specimens. Some measurements by C. S. Taylor on high purity alloys in wrought form are given in Table I.

Table 1
Electrical Resistivity of High Purity Aluminum-Silicon Alloys
Iron and Copper Less Than 0.05%

% Silicon	Resistivity Microhms per cm. cube*	Resistivity, Microhms per cm. cube, annealed†
0.02 or less	2.68	2.68
0.06	2.778	2.778
0.14	2.847	2.770
0.16	2.860	2.769
0.23	2.947	2.776

*Heated 2 days at 495°C. (925°F.), quenched in cold water.

†Heated 2 days at 495°C., quenched in cold water, followed by annealing 100 days at 200°C.

Thermal Conductivity—The thermal conductivity of aluminum-silicon alloys¹ is affected in a marked manner especially at high silicon concentrations by the particle size and distribution of the silicon, the smaller the particles of silicon, the higher being the conductivity. The conductivity of sand castings in the condition of highest conductivity (annealed) decreases from about 0.39 cgs. units for the 5% silicon alloy to about 0.31 cgs. units for the 13% silicon alloy. Modification of the 13% silicon alloy with sodium increases the conductivity to 0.39 cgs. units. Similarly, the chill cast 5% silicon alloy by virtue of its fine structure has a conductivity of about 0.44 cgs. units.

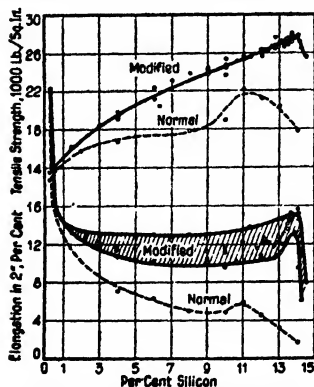


Fig. 6—Tensile properties of Al-Si alloys. Sand cast test bars $\frac{1}{2}$ in. dia.

Elastic Properties—The yield strengths of aluminum-silicon alloys are generally lower than those of aluminum-copper alloys of approximately the same tensile strength. This characteristic of the silicon alloys limits their use in some applications, but it is an advantage in others where some slight bending or forming operations must be carried out on castings. Few reliable data on the elastic limit have been published, but isolated determinations and general experience would place the true elastic limit of all aluminum-silicon alloy sand castings up to 14% silicon at not over 3,000 psi. The yield strength of modified sand castings varies from about 10,000 psi. at 8% silicon to 12,000 psi. at 14% silicon. A typical yield point for the normal sand cast 5% silicon alloy is about 9,000 psi. According to the determinations of Templin and Paul² the addition of silicon to aluminum results in a fairly uniform increase of Young's modulus in tension from about 10,250,000 psi. for the 5% silicon alloys to about 11,100,000 psi. for an alloy containing 13% silicon.

Tensile Properties—Fig. 6 gives the tensile properties of both normal and modified aluminum-silicon alloys in the form of $\frac{1}{2}$ in. dia. sand cast test bars.¹ These values represent laboratory determinations and the values given for modified alloys are those for material in which special care was taken to obtain the optimum effects of the modification process. Fig. 7 indicates the variation in tensile properties with silicon content of chill cast test bars.¹ Fig. 8 gives the tensile properties of 0.08 in. thick aluminum-silicon sheet in the hard rolled and annealed conditions.

Shearing Strength—The ultimate strength in double shear of the 5% silicon normal sand cast alloys is about 15,000 psi. For the modified 13% silicon alloy the shearing strength is about 18,000 psi.

Fatigue Resistance—Endurance limits for cast aluminum-silicon alloys containing from 5-14% silicon as given in the literature vary between 5,700 psi. and 9,500 psi. Results are not very concordant and the determinations were made on the basis of 5-50 millions of reversals. Determinations made in the Aluminum Research Laboratories on the basis of 500,000,000 cycles with the R. R. Moore type of rotating beam machine place the endurance limit of the normal sand cast 5%

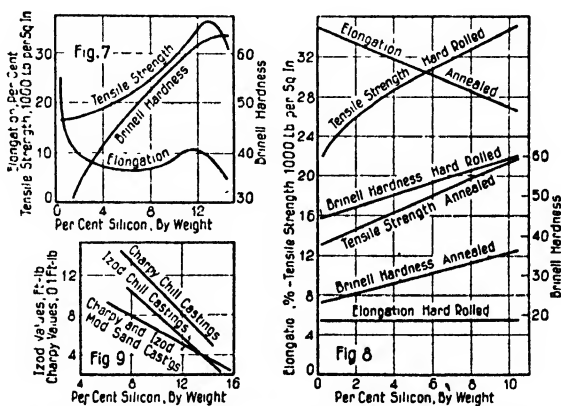


Fig. 7—Variation in tensile properties with Si content—chill cast test bars.

Fig. 8—Tensile properties of Al-Si sheet.

Fig. 9—Impact properties of Al-Si alloys.

silicon alloy at about 6,500 psi. The value for the modified 13% silicon alloy is about 6,000 psi.

Impact Properties—Fig. 9 from the data of Grogan⁸ and Stockdale⁹ gives the variation of impact resistance with silicon content of some modified sand and chill cast alloys.

Corrosion Resistance—Comparative experience in various fields indicates that the aluminum-silicon alloys preserve a better appearance under the conditions of ordinary atmospheric corrosion than do the aluminum-copper alloys. The rate of loss in mechanical strength of either of the types of alloys under these conditions is very low. Under conditions of salt spray corrosion, aluminum-silicon alloys appear to be definitely superior to the aluminum-copper alloys or the aluminum-copper-zinc alloys. They are, however, inferior under these conditions to the aluminum-magnesium alloys. Czocharski¹⁰ presents data on relative loss in weight in steam and nitric acid of the modified 13% silicon alloy, the 8% copper alloy, and the 12% zinc-2% copper alloy. All alloys were in the cast condition. Under these conditions the 13% silicon alloy is superior to the 8% copper, and the 12% zinc-2% copper alloys.

Casting Properties—The aluminum-silicon alloys are especially fluid, fill molds better, and take sharper impressions than any of the other common alloys of aluminum. For the normal alloys, the fluidity increases with silicon content up to the composition of the eutectic, about 11.6% silicon, and about 12-14% silicon for the modified alloys. Alloys containing upwards of about 3% silicon and with iron and copper in concentrations usual in ordinary commercial virgin ingot are unusually

free from hot shortness. This valuable property improves with increasing silicon content up to the eutectic composition, but all of the alloys containing from 5-13% silicon can be cast readily without cracking. The 5% silicon alloy is comparatively easy to feed, but as the silicon increases the alloys become subject to a peculiar type of internal shrinkage, and careful feeding is necessary in the case of alloys of high silicon contents. The ratio volume of risers to volume of castings should, in general, be greater in the case of the 13% silicon alloys than in the case of the 8% copper alloy. Because of their freedom from hot shortness and the characteristic tendency to form a sound outer layer or skin, the aluminum-silicon alloys are especially suitable for the production of castings which must be free from leaks.

Welding Rod—Some of the properties which make the aluminum-silicon alloys so valuable in the castings field have also been responsible for their wide use as welding rod. An alloy containing about 5% silicon is widely used for welding both cast and wrought products. Such rod is utilized in the cast and wrought forms, depending on the personal preference of the operator and the type of welding being done.

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Properties of Aluminum-Silicon (13%) Casting Alloys

By H. J. Rowe*

An aluminum-silicon alloy containing silicon in excess of the normal eutectic value,† if properly modified or treated prior to casting to insure solidification without the separation of visible particles of primary silicon, possesses mechanical properties considerably in excess of those obtained with an alloy of low silicon content. This modification may be produced by rapid cooling as in the die casting process** or, if sand cast, by the controlled addition of certain modifying agents such as sodium.†† The most common alloy of this type contains approximately 13% silicon with the balance aluminum. The properties of this alloy are as follows:

Physical Properties of Aluminum-Silicon Alloys (13% Si)

	Sand Cast	Die Cast
Ultimate tensile strength, psi. (min. to average ¹)	24,000-26,000	28,000-33,000
Yield strength, psi. (average ¹)	11,000	18,000
Elongation, % in 2 in. (min. to average)	5.0-8.0	1.0-2.0
Brinell hardness, 10 mm. ball, 500 kg. load	45-60	65-80
Rockwell hardness, 1/8 in. ball, 100 kg. load	E48-E72	.. ..
Yield strength in compression, psi. (approx. ^{2,3})	11,000	.. ..
Shearing strength, psi. (approx. ⁴)	18,000	.. ..
Charpy impact resistance, ft.-lb. (approx. ⁵)	3.0	2.0
Endurance limit, psi. (approx. ⁶)	6,000	15,000
Modulus of elasticity, psi. (approx.)	10,300,000	10,380,000
Specific gravity (approx.)	2.66	2.66
Weight per cu. in., lb. (approx.)	0.096	0.096
Pattern maker's shrinkage, in. per ft.	.. ..	.. ..
Solidification range, °F.	1150-1070	1150-1070
Electrical conductivity, % of copper standard at 68°F. (approx. ⁷)	40	38
Thermal conductivity at 25°C., cgs units (approx. ⁸)	0.37	0.33
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.)	0.0000111	0.0000111

*The footnotes for this tabulation are the same as those given in the article "Properties of Aluminum-Copper Casting Alloys, Containing 8% Copper." Tension properties of Die Castings based on one-quarter inch diameter specimens.

Specifications

Source	Sand Castings	Die Castings	Ingot
Aluminum Co. of America	No 47	No. 13	No 47
American Society for Testing Materials	B-26-3TT	B-85-3TT	B-58-3TT
Society of Automotive Engineers	Alloy K	Alloy V	Alloy K
U. S. Army	No 37	No. 305	.. ..
	.. ..	57-93-1B	.. ..

General Properties and Uses—The modified 13% silicon alloy has found considerable application in Europe, and in this country in certain foundries where heat treating equipment for the production of high strength heat treated alloys is not available. Such alloys as "Silumin" and "Alpax," both of this general composition, are still being used extensively in foreign foundries. However, with the newer heat treated alloy developments in this country,† the modified 13% silicon alloy is rapidly being replaced for sand casting work.

If proper care is taken during alloying and modification to prevent excessive oxidation, this alloy possesses many of the same desirable casting characteristics as does the 5% silicon alloy. It casts well in intricate, thin sections requiring pressure tightness, and has very good corrosion resistance. Since the beneficial effect of the modification process is largely lost on the remelting of this alloy, a retreatment of the metal is necessary if the resulting castings are to possess the properties of the modified alloy. The machinability of the 13% silicon alloy, as judged by the surface finish, is not so good as that of the aluminum-copper alloys.

The 13% silicon alloy is used for marine, automotive, steam radiators, water jackets, and manifold castings. For die castings, the 13% silicon alloy is generally preferred for large intricate castings with thin sections, because it combines good mechanical properties with excellent casting characteristics.

*Technical Dept., Castings Div., Aluminum Co. of America, Cleveland.

†See in this Handbook the article, "Constitution of Aluminum-Silicon Alloys."

**U. S. Patent No. 1,572,459.

††U. S. Patent Nos. 1,387,900 and 1,410,461.

‡See in this Handbook the article "Properties of Aluminum-Silicon-Magnesium Alloy."

Properties of Aluminum-Silicon (5%) Casting Alloys

By H. J. Rowe*

Aluminum-silicon alloys, because of their exceptional casting characteristics in intricate castings, find a large field of application. Such alloys, containing from 3-12% silicon,[†] are quite fluid at temperatures almost down to the freezing point and have a lower solidification shrinkage than the common aluminum-copper alloys. This combination of properties, together with excellent corrosion resistance, makes aluminum-silicon alloys particularly well suited for the production of dense, leak-proof castings, resistant to corrosive conditions. The properties of the most common of these alloys, one containing approximately 5% silicon and 95% aluminum, are as follows:

Physical Properties of Aluminum-Silicon (5%) Casting Alloy

	Sand Cast	Permanent Mold Cast	Die Cast
Ultimate tensile strength, psi. (min. to average) ¹	17,000-19,000	21,000-23,000	25,000-29,000
Yield strength, psi. (average) ²	9,000	10,000	13,000
Elongation, % in 2 in. (min. to average).....	3 0-6 0	2 5-9 0	3 5
Brinell hardness, 10 mm. ball, 500 kg. load.....	35-50	40-55	40-55
Rockwell hardness, 1/2 in. ball, 100 kg. load.....	E10-E60	E44-E65	E44-E65
Yield strength in compression, psi. (approx.) ^{3,4}	12,000	11,000	.....
Shearing strength, psi. (approx.) ⁴	14,000	18,000	.....
Charpy impact resistance, ft.-lb. (approx.) ⁵	1 0	2 1	4 0
Endurance limit, psi. (approx.) ⁶	6,500	.....	.....
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000	10,300,000
Specific gravity (approx.).....	2.65	2.68	2.70
Weight per cu.in., lb (approx.).....	0.098	0.097	0.097
Pattern maker's shrinkage, in. per ft.....	3/32	.....	.....
Solidification range—°F.	1165-1070	1165-1070	1165-1070
Electrical conductivity, % of copper standard at 68°F. (approx.) ⁷	37	41	41
Thermal conductivity at 25°C., cgs. units (approx.) ⁷	0.34	0.38	0.38
Coefficient of thermal expansion, °F. (68-212°F.) (approx.)	0.0000122	0.0000122	0.0000122

*The notes for this table are the same as those given in the table "Physical Properties of Aluminum-Copper (8%) Casting Alloys."

Specifications

Source	Sand Castings	Permanent Mold Castings	Die Castings	Ingot
Aluminum Co. of America	No. 43	No. 43	No. 43	No. 43
S.A.E.	SAE 35	SAE 35	SAE 304	.....
A.S.T.M.	B26-3TT	B108-3TT	B95-1TT	B58-3TT
U. S. Navy.....	{ Alloy 1 or JJ	Alloy 9 or 9A	Alloy IV	Alloy J or JJ
	{ 46A1e			46A5c
	{ Class 2			Class 2
U. S. Army.....	57-72 Grade 1		57-93-1B	.....
Federal.....	QQ-A-601			QQ-A-371 Class 2

General Properties and Uses—In addition to the casting characteristics and corrosion resistance, the 5% silicon alloy also possesses fair mechanical properties suitable for many engineering applications. The yield strength-tensile strength ratio is, however, somewhat lower than that of the common aluminum-copper alloys, and the machinability inferior because of the tendency of tools to drag the surface. This latter property can be materially overcome with the proper tool set-up. To insure maximum corrosion resistance, it is quite essential that a minimum of impurities be maintained in this alloy.

The properties of the 5% silicon alloy are ideal for use in marine castings, manifolds, water jackets, aircraft fittings, automotive body sections, meter cases, miscellaneous thin sections, and intricate castings where a minimum of machining is required and the mechanical properties are adequate. This alloy is also especially suited for architectural and ornamental castings of thin sections which require fine sharp details and which are subject to continuous atmospheric exposure. The 5% silicon alloy is likewise readily cast in permanent molds and dies.

*Technical Dept., Castings Div., Aluminum Co. of America, Cleveland.

†R. S. Archer, L. W. Kempf, and D. B. Hobbs, Heat Treatment of Aluminum-Silicon Alloys, Trans., Inst. Metals Div., A.I.M.E., 1928, v. 78, p. 198.

‡U. S. Patent 1,872,489.

Properties of Aluminum-Magnesium-Chromium Alloy

By F. Keller*

General Description—The aluminum-magnesium-chromium alloy designated "52S" has moderate strength combined with good resistance to corrosion, good workability, and high fatigue resistance. It is not susceptible to solution heat treatment, but can be strengthened and hardened by cold working.

Physical Properties—The sp.gr. of the alloy is 2.67. One cu.in. weighs 0.096 lb. The electrical conductivity, expressed in percentage of the "International Copper Standard", is 35. The thermal conductivity at 100°C. in cgs. units is 0.32.

Composition—The alloy has the following nominal composition: Magnesium, 2.5%; chromium, 0.25%; and aluminum, plus normal impurities, the balance.

Temper Designation—Only the annealed, intermediate, and hard rolled tempers of this alloy are produced. The temper is designated by a symbol or symbols following the alloy designation as explained in the article entitled "Commercially Pure Wrought Aluminum".

Mechanical Properties—The tensile and yield strength of this alloy is appreciably higher than for commercially pure wrought aluminum and wrought aluminum-manganese alloys. In the hard rolled temper, the alloy has a yield strength comparable with that of the heat treated strong aluminum alloys. Typical mechanical properties of this alloy in its various tempers are given in Table I.

Resistance to Corrosion—All of the tempers of this alloy have excellent resistance to corrosion. This alloy is particularly resistant to corrosion by salt water.

Workability—The alloy has good workability and in the annealed temper it is suitable for severe drawing and forming operations. The workability of the intermediate and full hard tempers decreases in proportion to the amount of cold reduction similar to other cold worked aluminum alloys.

Welding Characteristics—The methods commonly employed for welding other aluminum alloys can be used successfully. The torch welding characteristics are fair, while the resistance welding characteristics are excellent.

Annealing Treatment—This alloy can be annealed by heating to a temperature of 750°F., after which it should be withdrawn from the furnace and cooled in air.

Forms Produced—The forms in which this alloy is available are: Sheet, plate, wire, rod and bar, tubing and pipe.

Applications—This alloy finds general application for formed articles, for marine applications, and for structural uses where good workability, moderate mechanical properties, high fatigue strength, and good resistance to corrosion are desired.

Table I
Typical Mechanical Properties of Aluminum-Magnesium-Chromium Alloy¹ (52S)

Temper	Yield Strength ¹ (Set = 0.2%) Psi.	Ultimate Strength, Psi.	Elongation, ² % in 2 in. Sheet Specimen ($\frac{1}{8}$ in. Thick)		Round Specimen (0.505 in. Dia.)	Brinell Hardness 500 Kg. Ball 10 Mm. Ball	Shearing Strength ⁴ , Psi.	Endurance Limits ⁵ , Psi.	Approx. Radii for 90° Cold Bend ⁶
52S-O	14,000	29,000	25	30	45	18,000	17,000	0	
52S- $\frac{1}{4}$ H	26,000	34,000	12	18	62	20,000	18,000	0	-1½
52S- $\frac{1}{2}$ H	29,000	37,000	10	14	67	21,000	19,000	1	-3
52S- $\frac{3}{4}$ H	34,000	39,000	8	10	74	23,000	20,000	1½-4	
52S-H	36,000	41,000	7	8	85	24,000	20,500	3	-8

¹Young's modulus of elasticity is approximately 10,300,000 psi.

²Stress which produces a permanent set of 0.2% of the initial gage length. (A.S.T.M. Specification, Methods of Tension Testing, E 8-33.)

³Elongation values vary with the form and size of tension test specimen. Thin sheet has somewhat lower elongation than values for $\frac{1}{8}$ in. sheet shown in table. Thicker material, from which standard round tension test specimens (0.505 in. dia.) are tested, may have lower elongation because of the effect of commercial flattening operations on this property.

⁴Single shear strength values obtained from double shear tests.

⁵Based on withstanding 500,000,000 cycles of completely reversed stress, using the R. R. Moore type of machine and specimen.

⁶Bend radii expressed in terms of t =thickness of sheet. The minimum radii varies with the nature of the forming operation, type of forming equipment, and design and condition of tools, and with the thickness of the material.

*Aluminum Research Laboratories, New Kensington, Pa.

Properties of Aluminum-Copper-Iron-Magnesium Alloy Cast in Permanent Molds

By O. H. Heil*

This class of alloys was first developed for use in automotive pistons. Castings for this type of service are usually made in cast iron molds with steel cores. The rapid solidification results in mechanical properties appreciably higher than are obtained when the same alloy is cast in sand molds. Although slight modifications have been made in the original chemical composition (approximately 10% copper, 1% iron, and 0.25% magnesium¹) from time to time, the essential characteristics of the alloy have not been changed. Considerable improvement has been achieved by means of heat treatments, which can be grouped into two classes. Typical values for physical properties of the two classes are given in Table I.

Under "A" are listed properties for a typical high temperature solution heat treatment, followed by quenching and aging at a lower temperature. This type of treatment yields the highest combination of hardness and toughness. Other heat treatments of this type, with slight variations in time and temperatures used, result in slight changes of some of the figures quoted.

The rapid solidification accompanying casting in chill or "permanent" molds makes possible appreciable increases in hardness by "aging" or low temperature treatments alone. Hardness increases obtained in this manner are accompanied by corresponding decreases in toughness. It may be noted that values for Charpy impact resistance and percentage elongation are identical for the "A" and "B" treatments. This should not be interpreted as indicating equivalent toughness. Considerable data exist in the form of slow bend tests and practical experience indicates that for equivalent hardness the "A" treatment yields a product considerably tougher than the "B" treatment. Under "B" of the above table are

Table I
Properties of Al-Cu-Fe-Mg Alloy

	Heat Treatments	
	A	B
Ultimate tensile strength,* psi. (min. to average).....	40,000-48,000	30,000-35,000
Yield strength, ² psi. (average).....	36,000	31,000
Elongation in 2 in., % (min. to average).....	0-0.5	0-0.5
Brinell hardness, 10 mm. ball, 500 kg. load.....	125-150	95-125
Rockwell hardness, $\frac{1}{8}$ in. ball, 100 kg. load.....	.....	E92-E102
Yield strength in compression, psi. (approx.).....	36,000	31,000
Ultimate compressive strength, ³ psi. (approx.).....	89,000	87,000
Shearing strength, ⁴ psi. (approx.).....	30,000	25,000
Charpy impact resistance, ⁵ ft.-lb. (approx.).....	0.7	0.7
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000
Sp. gr. (approx.).....	2.89	2.89
Weight per cu.in., lb. (approx.).....	0.104	0.104
Pattern maker's shrinkage** (in. per in.).....	0.007	0.007
Solidification range, °F.....	1160-1004	1160-1004
Electrical conductivity, ⁷ % of copper standard at 68°F. (approx.)..	33	37
Thermal conductivity ¹ at 25°C., cgs. units (approx.).....	0.31	0.34
Coefficient of thermal expansion per °F. (68-212°F.) (approx.).....	0.0000122	0.0000122

¹U. S. Patent 1,732,557.

²Footnotes 2, 3, 4, 5, and 7 for this tabulation are the same as those given in the article, "Properties of Aluminum-Copper Casting Alloy, Containing 8% Copper."

³Tension values determined from $\frac{1}{2}$ in. dia. specimens, separately cast in permanent molds and tested without machining off the surface.

⁴**Pattern maker's allowance as listed is dimensional allowance used in finishing molds.

Specifications

	Alloy "A"	Alloy "B"	Ingot
Aluminum Company of America.....	No. 122-T65	No. 122-T52	No. 122
American Society for Testing	B108-38T	B108-38T	B112-38T
Materials	Alloy 4	Alloy 4	Alloy 4
Society of Automotive Engineers.....	No. 34	No. 34	.....
Federal .....	.....	.....	QQ-A-371 Class 6

*Technical Department, Castings Division, Aluminum Co. of America, Cleveland.

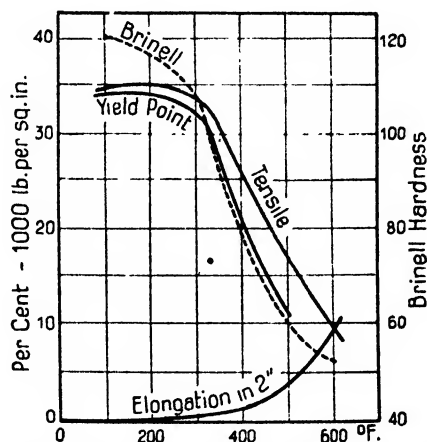


Fig. 1—Tensile properties of aluminum-copper-iron-magnesium (122) alloy at elevated temperatures. Brinell hardness at room temperature following stabilizing and testing at elevated temperatures.

listed typical properties for this type of treatment. Changes in time and temperature here will also result in slight deviations of some of the properties from those mentioned in the table.

General Properties and Uses—Alloys of this type combine satisfactory casting properties, good machining characteristics, and good mechanical properties at piston operating temperatures. Fig. 1 gives the variation with temperature of the tensile properties of specimens cast in permanent molds and originally in the "B" condition. Before testing, the specimens were held (40-150 days) at the temperature being investigated until no further change in properties could be detected. The Brinell hardness was determined at room temperature after stabilizing and testing at the elevated temperature.

In addition to its primary use in pistons, this alloy is utilized in other places where good machinability, high hardness and wear resistance are desired. Such applications are valve guides, typewriter parts, and sole plates for flatirons.

Properties of Aluminum-Copper-Magnesium-Manganese Alloy

(17S or Duralumin)

By P. V. Faragher*

General—An aluminum-copper-magnesium-manganese alloy, commonly called 17S or duralumin, is the oldest of the duralumin type alloys, several of which are now in commercial production. Some of the newer alloys possess definite advantages for certain purposes, but this alloy is still generally used in a great variety of products. For applications requiring good forming capacity and for which lower physical properties are acceptable, a modified composition designated A17S is available. This alloy is being used extensively in rivets because they can be driven in the fully heat treated and aged temper.

Composition—These alloys have the following nominal compositions in per cent:

	17S	A17S
Copper	4.0	2.5
Magnesium	0.5	0.3
Manganese	0.5	...
Aluminum plus normal impurities*.....	Remainder	Remainder

*Iron and silicon are always present in commercial aluminum ingot used in the manufacture of these alloys in amounts up to a max. of 1%. The silicon is an essential constituent of the alloy in the amounts normally present.

Specific Gravity—The sp.gr. of these alloys and their density in lb. per cu.in. are as follows:

	17S	A17S
Sp. gr.....	2.79	2.74
Density, lb. per cu.in.....	0.101	0.099

Temper Designation—These alloys are designated by the principal manufacturer by a number, followed by the letter "S" to indicate that they are wrought products. The number may be preceded by a letter to indicate a modification of the original alloy composition, such as A17S. The letter or letters designating the temper follow the alloy symbol, separated from it by a dash.

The "soft" or "annealed" temper is designated by the letter "O"; the heat treated temper by the letter "T"; and the temper resulting from cold working the material after heat treatment by the letters "RT". There is but one heat treated temper, since these alloys age harden at room temperatures.

Physical Properties—Typical mechanical properties of these alloys are shown in Table I. (Obviously these typical average values cannot be used as minimum values for purchase specifications.)

Table I

Typical Mechanical Properties of Aluminum-Copper-Magnesium-Manganese Alloys

Alloy	Temper	Tensile Strength, psi.	Yield Strength, psi.	Elongation, % in 2 in.	Shear Strength, psi.
17S	O	26,000	10,000	20	18,000
17S	T	60,000	37,000	20	36,000
17S	RT	65,000	47,000	13	38,000
A17S	O	22,000	8,000	24	15,000
A17S	T	43,000	24,000	24	25,000
Alclad 17S	T Sheet	56,000	33,000	18	32,000
Alclad 17S	RT Sheet	57,000	40,000	11	32,000

Corrosion Resistance—These alloys present considerable resistance to corrosion under most atmospheric conditions, but as a precaution, it is common practice in structural work to apply protective paint coatings. For severe conditions (under exposure to salt spray) sheet and wire are available with a core of 17S alloy and surfaces of pure aluminum, or of a highly corrosion resistant alloy which is anodic to the base alloy. The surface layers are alloyed and integral with the underlying

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17S core and protect it, both by preventing contact with the corrosive medium, and by electrolytic action: Thus protected, sheet and wire are sold under the trade marked name "Alclad".

Workability—In the soft temper these alloys can be subjected to severe forming operations. In the fully heat treated temper, greater radii are required for bends, and less depth of drawing is possible than in the soft temper or immediately after quenching. The modified composition, A17S-T, withstands more severe working than 17S-T. By choosing proper radii for bends and suitable tools, 17S-RT can be formed into various structural shapes without difficulty. If 17S is quenched from the heat treating temperature and formed in less than 2 hrs. before aging occurs, it is only slightly less workable than in the soft temper. By storing at a temperature below 32°F., greater workability can be retained for a day or more. "Alclad" sheet can be bent around a smaller diameter than uncoated sheet of the same gage and temper.

Welding—Spot welding is coming into use for joining these alloys in the gages for which this process is applicable. They can be welded by the torch and arc welding processes, but the mechanical properties and resistance to corrosion of the metal adjacent to the welds are lowered and must be restored by heat treatment of the assembly. The cast metal in the weld does not develop as high properties as the wrought alloy, which fact must be considered when designing the joint. Other methods of joining are commonly used.

Heat Treatment—These alloys are heat treated by heating at a temperature of 930-950°F. The time of heating varies with the thickness of the metal and the heating medium. After heating, the alloy is quenched in cold water. The interval between removing the metal from the heating medium and completely immersing it in the water should be as short as possible, at most several seconds. Aging takes place at room temperature, the rate gradually decreasing for about four days when it is practically completed. Aging may be retarded by cooling the alloys below 32°F., but it proceeds at the normal rate when they are warmed to room temperature. "Alclad" material should be heated the shortest length of time which will produce desired properties. If Alclad sheet is heated too long there will be too great diffusion of the alloying elements of the core into the surface layer, with consequent injury to the protecting qualities of the latter.

Annealing—The annealing practice varies with the condition of the alloy and the result desired.

(a) Material originally in the soft temper which has been hardened by cold forming, can be annealed completely by heating it to 640-670°F., and cooling.

(b) Material in the heat treated temper, whether subsequently cold worked or not, will have most of the effects of heat treatment removed by following the practice described in paragraph (a). For severe forming which requires completely softened material, the following practice is necessary.

(c) For the complete annealing of alloys in the heat treated (T) temper, whether or not they have been subsequently strain hardened, heat the metal for 2 hr. at a temperature of 750-800°F., and then cool slowly. The rate of cooling to 500°F. should not exceed 50°F. per hr. The rate of cooling below 500°F. is unimportant.

Commercial Forms—The alloy 17S is available commercially in all of the usual wrought forms such as sheets, plates, tubes, rods, bars, wire, rolled and extruded shapes, forgings, rivets, bolts, nuts, machine screws, and other screw machine products. The alloy A17S is produced only in rivets.

Properties of Wrought Aluminum-Copper-Magnesium (1.5%) Manganese Alloy

By T. W. Bossert* and J. A. Nock, Jr.†

General—The aluminum-copper-magnesium-manganese alloy, known as 24S, is a heat treatable wrought aluminum alloy having mechanical properties superior to those of 17S with workability slightly inferior to that of 17S in the "T" and "RT" tempers. The alloy was developed particularly for the aircraft field. After solution heat treatment, the alloy age hardens spontaneously at room temperature. Like 17S, this alloy may be had in the Alclad¹ form.

Composition—The nominal composition of the alloy is copper 4.4%, magnesium 1.5, manganese 0.6, and balance aluminum.

Specific Gravity—The specific gravity of this alloy is 2.76.

Temper Designation—The temper in which this alloy is supplied is designated by a symbol or symbols following the alloy designation.

In both bare and Alclad form, this alloy is supplied in three tempers; namely, annealed, designated by the suffix "O"; heat treated and aged (at room temperature), designated by the suffix "T"; and heat treated, aged, and cold worked a definite amount, designated by the suffix "RT".

Mechanical Properties—Typical mechanical properties for both the bare and Alclad forms are given in Table I.

Table I
Properties of 24S Aluminum Alloy

Temper	Tensile Strength, psi.	Yield Strength, psi.	Elongation, % in 2 in.	Brinell Hardness	Shear Strength, psi.	Endurance Limit* psi.
-O	26,000	10,000	20	42	18,000	12,000
-T	68,000	44,000	19	105	41,000	18,000
-RT	70,000	55,000	13	116	42,000	.....

Alclad 24S Sheet

-O	25,000	10,000	18	...	.....	.....
-T	62,000	41,000	18	..	40,000	.....
-RT	66,000	50,000	11	...	41,000	.....

*Based on the material withstanding 500 million cycles of stress.

Corrosion Resistance—The maximum corrosion resistance of both forms of this alloy is developed in the heat treated, or in the heat treated and rolled tempers. These materials are not intended for use in the annealed temper, but the metal may be obtained in this temper for drawing or for severe forming operations which are then followed by heat treatment.

The bare alloy has a corrosion resistance which is similar to that of 17S. The same protective measures against corrosion that apply to 17S should be observed in using 24S.

The Alclad form of the alloy has, because of the pure aluminum coating, excellent corrosion resistance and can generally be used without additional protective coating.

Workability—In the annealed temper both forms of this alloy are reasonably workable. The material can be formed over sharp radii and can be drawn to a limited extent. Annealed material is, therefore, often specified and the material, after working, is heat treated to develop its characteristic properties. The heat treated tempers of these materials are not suitable for drawing, but can be formed over a bend radius equal to 1-6 times² the material thickness. This alloy is more

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¹The Alclad form of 24S alloy consists of the high strength core covered on both sides with a layer of high purity aluminum.

²The multiple bend radius increases from 1-6 times the thickness as the thickness of the piece itself increases.

workable immediately after quenching and the more difficult bends may be made in this manner.

Welding—This alloy, and particularly Alclad 24S, may be satisfactorily welded by electric resistance methods. It is not suitable, however, for torch or arc welding.

Solution Heat Treatment—The solution heat treatment of all forms of this alloy consists of heating the stock to 915-930°F. in a fused nitrate bath or suitable air furnace. The time at this temperature is determined by the thickness of the section. The alloy is quenched in cold water with the minimum of delay between removal from the heat treating medium and immersion in the quenching water.

No elevated temperature aging is required for this alloy, as the material develops its normal heat treated properties by spontaneous aging; in fact, such elevated temperature aging is to be avoided.

Annealing—The alloy is annealed by heating to 650°F. for about 2 hr. and then cooling normally in air.

Forms Produced—This alloy is available in the form of sheet, rod, bar, extruded shapes, tubing, rivets, and wire. The Alclad form of this alloy is furnished in sheet form only.

Applications—Both forms of this alloy are used where maximum strength is desired with minimum weight. Its use in aircraft construction particularly is indicated, but its applications are not entirely limited to this field.

Properties of Aluminum-Copper-Nickel-Magnesium Alloy Cast in Permanent Molds

By O. H. Hell*

This alloy, sometimes known as "Y" alloy,¹ finds its most extensive use in this country in the form of castings for aircraft and Diesel motor pistons. To a lesser extent it is used for outboard motor pistons. Castings for this type of service are usually made in cast iron molds with either steel or sand cores. The rapid solidification results in mechanical properties appreciably higher than are obtained

Table I
Physical Properties of Al-Cu-Ni-Mg Alloy

	Heat Treatments	
	A	B
Ultimate tensile strength, ¹ psi. (min. to average).....	40,000-47,000	34,000-40,000
Yield strength, ² (average).....	42,000	34,000
Elongation, % in 2 in. (min. to average).....	0-0.5	0.0
Brinell hardness, 10 mm. ball, 500 kg. load.....	100-130	90-120
Rockwell hardness, $\frac{1}{2}$ in. ball, 100 kg. load.....	E94-E108	E90-E102
Yield strength in compression, psi. (approx.).....	48,000	34,000
Ultimate compressive strength, ³ psi. (approx.).....	76,000	81,000
Shearing strength, ⁴ psi. (approx.).....	31,000	26,000
Charpy impact resistance, ⁵ ft.-lb. (approx.).....	0.6	0.6
Endurance limit, ⁶ psi. (approx.).....	9,500	
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000
Sp. gr. (approx.).....	2.77	2.77
Weight per cu.in., lb. (approx.).....	0.100	0.100
Pattern maker's shrinkage, ⁷ in. per in.....	0.007	0.007
Electrical conductivity, ⁷ % of copper standard at 68°F. (approx.)..	33	34
Thermal conductivity at 25°C., cgs. units (approx.).....	0.31	0.32
Coefficient of thermal expansion per °F. (68-212°F.) (approx.).....	0.0000125	0.0000125

*Footnotes for 1, 2, 3, 4, 5, 6 and 7 are the same as those given in the article, "Properties of Aluminum-Copper Casting Alloy, Containing 8% Copper."

*Pattern maker's allowance as listed is dimensional allowance used in finishing molds.

Specifications

Source	Alloy "A"	Alloy "B"	Ingot
Aluminum Company of America.....	No. 142-T61	No. 142-T571	No. 142
American Society for Testing	B108-38T	B108-38T	B112-38T
Materials	Alloy 11	Alloy 11	Alloy 11
Society of Automotive Engineers.....	No. 39	No. 39	.....
U. S. Army (Sand cast).....	57-72-B	.....	.....
	Grade A	.....	.....

when the same alloy is cast in sand molds. The nominal chemical composition is 4% copper, 2% nickel, and 1.5% magnesium. The piston castings are usually heat treated. The heat treatments used can be grouped into two classes. Typical values for physical properties of the two classes are given in Table I.

Under "A" are listed properties for a high temperature solution heat treatment followed by quenching and aging at a lower temperature. This treatment yields the highest combination of hardness and toughness.

The rapid solidification accompanying casting in chill or "permanent" molds makes possible appreciable increases in hardness by "aging" or low temperature treatments alone. Hardness increases obtained in this manner are accompanied by corresponding decreases in toughness. Under "B" of the above table are listed properties for this type of treatment.

General Properties and Uses—Heat treating effects in this alloy are unaccompanied by appreciable changes in density. This distinctive property is of value in structures, such as pistons, operating at elevated temperatures, since it insures practical stability of dimensions, other than the normal thermal expansion and contraction, regardless of the structural condition of the alloy. Fig. 1 shows the

*Technical Department, Castings Division, Aluminum Co. of America, Cleveland.

¹W. Rosenhain, S. L. Archbutt, and D. Hanson; Eleventh Report to the Alloys Research Committee of the Inst. of Mech. Engrs. (1921), on Some Alloys of Aluminum.

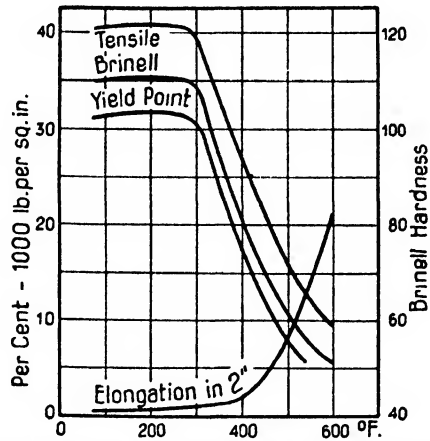


Fig. 1—Tensile properties of chill cast Al-Cu-Ni-Mg ("X") alloy at elevated temperatures. Brinell hardness at room temperature after exposure for tensile tests at elevated temperatures.

variation with temperature of the tensile properties of chill cast test bars of this alloy. The bars were originally in the "B" condition and were held at the temperature of testing until no further change in properties could be noted. The holding periods varied from 40-150 days. The Brinell hardness determinations were made at room temperature after the tensile tests at elevated temperatures.

Properties of Wrought Aluminum-Magnesium-Silicon Alloys

By F. Keller* and T. W. Bossert†

General—The aluminum-magnesium-silicon alloy (53S) is susceptible to solution heat treatment.^{1,2} It is formed easily and can be welded in the annealed and heat treated tempers. The alloy finds a wide field of application where moderate strength, good workability, and high resistance to corrosion are of prime importance. It is available in the form of sheet, plate, extruded shapes, tubing, rod, bar, wire, and rivets.

Composition—The alloy has the following nominal composition:

Silicon	0.7%
Magnesium	1.2%
Chromium	0.25%
Maximum total of other elements.....	0.55%
Aluminum	Balance

Specific Gravity—The specific gravity of the alloy is 2.69.

Temper Designations—The temper of wrought aluminum alloys is designated by a symbol or symbols following the alloy designation as explained in the article entitled "Commercially Pure Wrought Aluminum."

Mechanical Properties—Typical mechanical properties of the alloy in various tempers are given in Table I.

Resistance to Corrosion—The alloy in all of its various tempers shows excellent resistance to weathering and corrosion and is particularly suitable for those applications where such characteristics are essential.

Workability—The annealed temper of this alloy is adapted for severe drawing and forming operations. The workability of the intermediate and full hard tempers is decreased in proportion to the amount of cold reduction and the softer intermediate tempers have excellent working characteristics. After a solution heat treatment the alloy possesses satisfactory workability for all but the more severe drawing or forming operations. Precipitation heat treatment decreases the workability, but may be accomplished after forming the heat treated material without causing distortion.

Table I
Mechanical Properties¹ of Aluminum-Magnesium-Silicon Alloy

Temper Designation	Tensile Strength, psi.	Yield Strength, ² psi.	Elongation, % in 2 in.	Brinell Hardness ³ No.
O (Annealed)	16,000	7,000	25	26
½H	22,000	21,000	8	40
H (hard)	28,000	26,000	6	48
W ⁴	33,000	20,000	22	65
T ⁵	39,000	33,000	14	80
T ⁶	28,000	20,000	14	54
T5 ⁶				

¹Young's Modulus is approximately 10,000,000 psi.

²Stress at which stress strain curve departs 0.2% from the initial modulus line produced.

³10 mm. ball, 500 kg. load.

⁴Temper produced by solution heat treatment.

⁵Temper produced by precipitation heat treatment.

⁶Special temper available only in extruded forms.

Welding Characteristics—This alloy can be welded by the methods commonly used for welding the other aluminum alloys.

Heat Treatment and Aging—The recommended temperature range for the solution heat treatment is 960-980°F. The preferable precipitation heat treatment consists in heating for 18 hr. at 310-320°F.

Annealing Treatment—The practices commonly employed for annealing other aluminum alloys are suitable for this material.

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¹U. S. Pat. 1,473,739.

²E. H. Dix, Jr., F. Keller, and R. W. Graham, Equilibrium Relations in Aluminum-Magnesium-Silicon Alloys of High Purity, Trans., A.I.M.E., Inst. Metals Div., 1931, v. 93, p. 404.

Properties of Wrought Aluminum-Manganese-Magnesium Alloy

By T. W. Bossert* and J. A. Nock, Jr.†

General Description—The aluminum-manganese-magnesium alloy, known as 4S,¹ is a moderate strength alloy with good workability and very good corrosion resistance. It is not susceptible to hardening by heat treatment. In its harder tempers the yield strengths approach those of the strong heat treatable alloys, although the ultimate strengths are lower.

Specific Gravity—The specific gravity of this alloy is 2.72.

Composition—The nominal composition of the alloy is magnesium 1%, manganese 1.25% and the balance aluminum.

Temper Designation—This alloy is produced only in the annealed, intermediate and hard rolled tempers.

Tempers of aluminum alloys are designated by a symbol or symbols following the alloy designation. Thus the annealed temper is designated by the suffix "O", and the hard rolled temper by the suffix "H". Intermediate tempers are designated by fractions preceding the letter "H". The intermediate and hard rolled tempers are produced by cold working the alloy to definite extents after annealing.

Characteristics—Typical mechanical properties for the various tempers of the alloy are given in the following tabulation:

Temper	Tensile Strength, psi.	Yield Strength, psi.	Elong., % in 2 in	Brinell Hardness No.	Shear Strength, psi.	Endurance Limit, psi.
4S-O ...	26,000	10,000	20	45	16,000	14,000
4S-1/4H .	31,000	22,000	10	52	17,000	14,500
4S-1/2H .	34,000	27,000	9	63	18,000	15,000
4S-3/4H .	37,000	31,000	5	70	20,000	15,500
4S-H	40,000	34,000	5	77	21,000	16,000

Corrosion Resistance—The corrosion resistance of the aluminum-manganese-magnesium alloy is of the same order for all tempers, and is similar to that of commercially pure aluminum.

Workability—The annealed temper of this alloy will normally withstand drawing and forming operations of average severity. It will not form as readily as commercially pure aluminum. The workability decreases with increase of hardness, so that the full hard temper is suitable for but little drawing work, and requires rather generous bend radii.

Welding—This alloy can be joined by welding, using common commercial practice for aluminum and its alloys. To avoid cracking, care must be exercised in torch welding heavy sections.

Annealing—This alloy is annealed by heating to a temperature of 750°F., after which it should be withdrawn from the furnace and cooled in air.

Forms Produced—This alloy is furnished in sheet, plate, tubing, rod, bar, extruded shapes, wire, and rivets.

Applications—This alloy finds general application in the field of formed articles where medium strength, resistance to deformation and good corrosion resistance are important.

Its harder tempers are particularly applicable where lightness, high corrosion resistance, and resistance to permanent deformation are required, as in panel and siding stock.

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¹U. S. Patent 1,797,851.

Properties of Heat Treated Aluminum-Silicon-Copper-Magnesium Casting Alloys

By L. W. Kempf* and H. J. Rowet†

One of the alloys developed in the attempts to improve the mechanical properties of the binary aluminum-silicon alloys contains about 5% silicon, 1.25% copper, and 0.5% magnesium.^{1,2} This alloy retains the excellent casting characteristics of the binary aluminum-silicon alloys containing from 5-10% silicon and in addition is capable of developing by heat treatment superior mechanical properties. Castings of this alloy are produced with a number of different heat treatments. Some of the mechanical and physical properties obtained with each of these heat treatments are given in Table I.

General Properties and Uses—This alloy was developed for a rather specific field of application; namely, that of liquid cooled cylinder heads for internal combustion motors. It possesses the casting characteristics necessary for the economical production of castings of such complicated nature. Pressure tight castings are more easily produced than in any other casting alloy suitable for this purpose. The alloy maintains its mechanical properties well at temperatures in the neighborhood of 400°F. Thus short time tensile tests performed at 400°F. after extended exposure to that temperature gave average values of 18,000 psi. tensile strength and 3% elongation on metal originally in the "B" condition. Its corrosion resistance is not so good as that of the copper-free heat treated aluminum-silicon-magnesium alloy or that of the 5% aluminum-silicon alloy.

Various heat treatments as listed in the table of properties have been developed to provide a combination of properties satisfactory for many types of service. Where good strength, excellent ductility and toughness are desired, the high temperature solution heat treatment "A" is indicated. If higher hardness, yield and tensile strengths are more desirable than maximum ductility, the solution heat treatment should be followed by a precipitation treatment (B). An extended precipitation treatment following a solution treatment yields maximum hardness, yield and tensile strengths with correspondingly low elongation (C). A special heat treatment "D" consisting in a precipitation treatment alone has been developed for complicated castings with large variations in cross sectional area. If it is desirable to essentially stabilize the alloy as regards slight changes in density on reheating, a special precipitation heat treatment "E" may be applied.

This alloy has been successfully utilized in producing castings for liquid-cooled cylinder heads for automotive, aircraft, and Diesel engines, for water jackets, cylinder blocks and water-cooled exhaust manifolds.

The excellent casting characteristics of this alloy make it especially adaptable to the production of permanent mold castings. Castings so produced will show mechanical properties considerably higher than those of the same alloy cast in green sand.

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¹U. S. Patent 1,848,816.

²R. S. Archer and L. W. Kempf, "Aluminum-Silicon-Magnesium Casting Alloys," Trans., A.I.M.E., Inst. of Metals Div., 1931, v. 93, p. 448.

Table I
Properties of Heat Treated 5% Si, 1.25% Cu, 0.5% Mg Alloys

	"A"	"B"	Heat Treatment "C"	"D"	"E"
Ultimate tensile strength, psi. (min. to average) ¹	27,000-30,000	32,000-35,000	36,000-38,000	26,000-28,000	25,000-28,000
Yield strength, psi. (average).....	20,000	25,000	33,000	21,000	23,000
Elongation, % in 2 in. (min. to average).....	4.0-5.0	2.0-3.5	0.5-1.0	1.0-1.7	0-1.5
Brinell hardness, 10 mm. ball., 500 kg. load.....	50-65	65-85	80-95	60-80	50-70
Rockwell hardness, 1/8 in. ball., 100 kg. load.....	E60-E77	E77-E90	E87-E95	E72-E87	E60-E81
Yield strength in compression, psi. (approx. ²).....	23,000	29,000	36,000	25,000	24,000
Shear strength, psi. (approx. ³).....	28,000	30,000	.....	.....	22,000
Charpy impact resistance, ft.-lb. (approx. ⁴).....	1.3	1.1	0.8	.....	.....
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000	10,300,000	10,300,000	10,300,000
Specific gravity (approx.).....	2.68	2.68	2.68	2.68	2.68
Weight per cu. in., lb. (approx.).....	0.097	0.097	0.097	0.097	0.097
Pattern maker's shrinkage, in. per ft. ....	.....	.....	.....	.....	.....
Solidification range, °F. (approx.).....	1160-1075	1160-1075	1160-1075	1160-1075	1160-1075
Electrical conductivity, % of copper standard at 68°F. (approx. ⁵).....	35	36	37	36	43
Thermal conductivity, at 77°F., cgs. units (approx. ⁶).....	0.33	0.33	0.35	0.33	0.40
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.).....	0.000122	0.000122	0.000122	0.000122	0.000122
*Tension values determined from 1/2 in. dia. specimens, separately cast in green sand molds and tested without machining off the surface.					
†Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.					
‡Results of tests on specimens having l/r ratio of 12.					
§Single shear strength values from double shear test.					
||Charpy impact values as determined using 10 x 10 mm. specimens on modified Charpy machine with 5.07 lb. hammer.					
¶Based on specimens machined from bars individually cast in chill molds and free from porosity and internal defects.					

Specifications
(Sand Castings)

Source	"A"	"B"	Heat Treatment "C"	"D"	"E"
Aluminum Co. of America.....	No. 355-T4	No. 355-T6	No. 355-T61	No. 355-T5	No. 355-T51
U. S. Army.....	.....	No. 11307A	.....	.....	.....
U. S. Navy, No. M212a, Class 10.....	HT2	HT3	.....	.....	HT4
Society of Automotive Engineers.....	No. 322-HT1	No. 322-HT2	No. 332-HT3	.....	.....
American Society for Testing Materials B26-37T.....	.....	.....	.....	.....	.....
Alloy N.....	HT1	HT2	.....	.....	HT3

Properties of Heat Treated Aluminum-Silicon-Magnesium Casting Alloy

By L. W. Kempf* and H. J. Rowe†

The many advantages of the binary aluminum-silicon alloys for castings are accompanied by the disadvantage of relatively low strength. Attempts to overcome this disadvantage have led to the development of several heat treated alloys, one of which contains about 7% silicon and 0.3% magnesium.¹ When made of metal of sufficiently high purity, this alloy, following the proper heat treatment, develops tensile properties quite comparable with those of the heat treated aluminum-copper casting alloys. Table I gives the mechanical and physical properties of this type of alloy.

Table I
Physical Properties of Heat Treated 7% Si, 0.3% Mg Casting Alloy

	Heat Treatment	
	"A"	"B"
Ultimate tensile strength, psi. (min. to average) ¹	26,000-28,000	30,000-32,000
Yield strength, psi. ²	16,000	22,000
Elongation, % in 2 in. (min. to average).....	5.0-6.0	3.0-4.0
Brinell hardness, 10 mm. ball, 500 kg. load.....	50-70	60-80
Rockwell hardness, 1/4 in. ball, 100 kg. load.....	E60-E80	E72-E87
Yield strength in compression, psi. (approx. ^{3, 4}).....	18,000	22,000
Shearing strength, psi. (approx. ⁴).....	22,000	27,000
Charpy impact resistance, ft.-lb. (approx. ⁵).....	1.7	1.0
Endurance limit, psi. (approx. ⁶).....	.....	8,000
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000
Specific gravity (approx.).....	2.63	2.63
Weight per cu. in., lb. (approx.).....	0.095	0.095
Pattern maker's shrinkage, in. per ft.....	3/32	3/32
Solidification range, °F. (approx.).....	1130-1075	1130-1075
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.).....	0.0000119	0.0000119

¹Tension values determined from 1/2 in. dia. specimens, separately cast in green sand molds and tested without machining off the surface.

²Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.

³Results of tests on specimens having l/r ratio of 12.

⁴Single shear strength values from double shear tests.

⁵Charpy impact values as determined using 10 x 10 mm. specimens on modified Charpy machine with 5.07 lb. hammer.

⁶Endurance limit based on 500,000,000 cycles using R. R. Moore type rotating beam machine.

Specifications (Sand Castings)

Source	Heat Treatment	
	"A"	"B"
Aluminum Company of America	No. 356-T4	No. 356-T6
U. S. Army		No. 11308
U. S. Navy	46 Alc-Class 3	.....
Society of Automotive Engineers	No. 323-HT1	No. 323-HT2
	B26-37T	B26-37T
American Society for Testing Materials	Alloy M-HT1	Alloy M-HT2

General Properties and Uses—The casting characteristics of this type of alloy are fully equal to those of the binary aluminum-silicon alloys containing from 5-10% silicon. With a high temperature solution heat treatment (A) the alloy possesses the maximum combination of strength and ductility and this is the heat treatment to be used where toughness or shock-resisting ability is desired. If high hardness, yield and tensile strengths are more desirable than maximum ductility, the solution treatment is followed by a precipitation treatment (B). The corrosion resistance

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¹R. S. Archer and L. W. Kempf, Aluminum-Silicon-Magnesium Casting Alloys, Trans., A.I.M.E., Inst. of Metals Div., 1931, v. 93, p. 448.

of this alloy is somewhat superior to that of other commercial aluminum alloys containing substantial concentrations of copper.

This alloy has been used quite successfully in the same type of castings that have been produced satisfactorily from the heat treated 4% copper alloy. There are, however, inherent differences in the two types of alloys which should be noted. The aluminum-copper alloy with a solution heat treatment possesses a higher impact resistance than the aluminum-silicon-magnesium alloy under the same conditions. On the other hand, the aluminum-silicon-magnesium alloy has a corrosion resistance superior to that of the aluminum-copper alloy and also casting characteristics which are very much better. The latter permit the production of complicated or pressure tight castings which might be impractical in the heat treated aluminum-copper alloys. Such parts as automotive and Diesel engine crankcases, engine bases, transformer connector cases, and miscellaneous pneumatic tools and air compressor parts might be cited as suitable applications for the heat treated aluminum-silicon-magnesium alloy. The machinability of this type of alloy is quite satisfactory, being much better as regards surface finish than that of the binary un-heat treated aluminum-silicon alloys.

The excellent casting characteristics of this alloy make it quite adaptable to casting in permanent molds, and when so produced castings have mechanical properties considerably higher than when cast in sand.

Properties of Aluminum-Silicon-Nickel-Copper-Magnesium Alloy

(132 AND 32S)

By L. W. Kempf* and O. H. Heilt

This class of alloys was developed to meet the demand for a material with a lower coefficient of thermal expansion than the older alloy in general use for automotive pistons which contains about 10% copper. A preferred composition is 12-14% silicon, 1% copper, 1% magnesium, and 1-2% nickel.¹ Typical values for physical properties of the three classes of heat treatments are given in Table I.

Under "A" are listed properties for castings with a typical high temperature solution heat treatment followed by quenching and aging at a lower temperature. This type of treatment yields the highest combination of hardness and toughness. Other heat treatments of this type, with slight variations in time and temperatures used, result in slight changes of some of the figures quoted.

The rapid solidification accompanying casting in chill or "permanent" molds makes possible appreciable increases in hardness by "aging" or low temperature treatments alone. Hardness increases obtained in this manner are accompanied by corresponding decreases in toughness. Under "B" of Table I are listed typical properties for this type of treatment. Changes in time and temperature here will also result in slight deviations of some of the properties from those mentioned in the table.

Under "C" are listed typical properties of this type of alloy in the forged, solution heat treated, and aged condition. A large proportion of the aircraft pistons are now being produced by this process.

Table I
Properties of Al-Si-Ni-Cu-Mg Alloy

	Heat Treatments		
	"A"	"B"	"C"
Ultimate tensile strength,* psi.....	41,000-50,000	31,000-40,000	52,000-54,000
Yield strength, ² psi. (average).....	40,000	28,000	43,000
Elongation in 2 in., % (min. to average).....	0-0.5	0-1.5	5.0-8.0
Brinell hardness, 10 mm. ball, 500 kg. load.....	120-150	85-115	110-125
Rockwell hardness, ½ in. ball, 100 kg. load.....	E102-E118	E88-E100	E100-E115
Yield strength in compression, ³ psi. (approx.).....	.....	30,000	43,000
Ultimate compressive strength, ³ psi. (approx.).....	.....	60,000	54,000
Shearing strength, ⁴ psi. (approx.).....	.....	24,000	38,000
Charpy impact resistance, ⁵ ft.-lb. (approx.).....	0.7	0.7	1.3
Endurance limit, ⁶ psi. (approx.).....	.....	8,000	14,000
Modulus of elasticity, psi. (approx.).....	10,300,000	10,300,000	10,300,000
Sp. gr. (approx.).....	2.70	2.70	2.70
Weight per cu. in., lb. (approx.).....	0.097	0.097	0.097
Pattern maker's shrinkage,** in per in.....	0.004-0.007	0.004-0.007	.....
Solidification range, °F.....	1095-1000	1095-1000	1095-1000
Electrical conductivity, ⁷ of copper standard at 77°F.....	36	29	36
Thermal conductivity ⁷ at 25°C., cgs. units (approx.).....	0.34	0.28	0.34
Coefficient of thermal expansion, per °F. (68-212°F.) (approx.).....	0.0000105	0.0000105	0.0000105

*Tension values of "A" and "B" determined from ½ in. dia. permanent mold castings tested without machining off the surface; of "C" from ½ in. dia. specimens machined from forged stock.

**Pattern maker's allowance as listed is dimensional allowance used in finishing the metal molds.

¹Footnotes 2, 3, 4, 5, 6, and 7 for this tabulation are the same as those given in the article, "Properties of Aluminum-Copper Casting Alloy, Containing 8% Copper."

Specifications

Source	Alloy A	Alloy B	Alloy C
Aluminum Co. of America.....	A132-T65	A132-T651	32S-T
U. S. Navy (Sand cast).....	M212a Class 12HT4	M212a Class 12HT2	.....
U. S. Army.....	.....	.....	57-153-D
Society of Automotive Engineers.....	No. 321	No. 321	.....
American Society for Testing Materials.....	B108-3TT Alloy 6	B108-3TT Alloy 6

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⁷Technical Department, Castings Division, Aluminum Co. of America, Cleveland.

¹U. S. Patent No. 1,799,837.

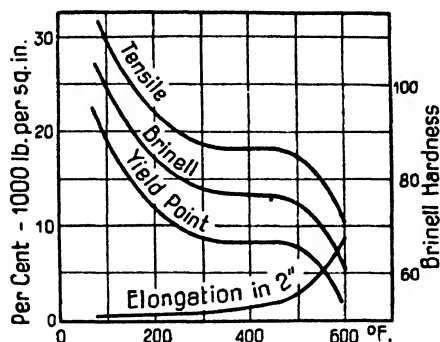


Fig. 1—Tensile properties of chill cast aluminum-copper-magnesium-nickel-silicon (132) alloy at elevated temperatures. Brinell hardness at room temperature after stabilization and testing at elevated temperatures.

General Properties and Uses—In addition to the relatively low coefficient of thermal expansion, this alloy possesses other properties which recommended its use for pistons. These are low specific gravity, which makes it especially acceptable to the aircraft industry, high hardness and excellent bearing properties. Like the aluminum-copper piston alloys, it retains a large percentage of its mechanical properties at the elevated temperatures existing in internal combustion motor pistons as is evident from Fig. 1. The test specimens used in determining the properties on which these curves are based were cast in permanent molds and originally in the "B" condition were held at the temperature of testing until no further change in properties could be noted. The holding periods varied from 40-150 days. The Brinell hardness determinations were made at room temperature after the stabilization and testing at elevated temperatures.

The machining properties of this alloy are not equal to those of the aluminum-copper alloys. With the use of tungsten carbide tools, however, large quantities of these pistons are being machined without difficulty.

This alloy possesses casting characteristics differing from those of the older aluminum-copper piston alloys. One of the most important is its greater tendency toward internal shrinkage in heavy sections. A casting technique has been developed which overcomes this tendency and makes possible the quantity production of sound castings.

Properties of Wrought Aluminum-Silicon-Magnesium Alloy

L. W. Kempf* and J. H. Alden**

General—An aluminum-silicon-magnesium alloy (51S†) is widely used in the wrought form. It is characterized by excellent hot workability and is susceptible to heat treatment. It can be coldformed easily, particularly in the annealed (O) and solution heat treated (W) tempers. In the fully heat treated temper (T) the yield strength is somewhat higher than that of duralumin (17S).

Composition—The nominal composition of this alloy is silicon 1.00%, magnesium 0.6%, and the balance aluminum, plus impurities. Iron and copper are always present in ingots used in the manufacture of this alloy.

Temper Designation—The temper of this alloy is designated by a symbol or symbols following the number used to designate the alloy composition and the letter S, which indicates that it is a wrought alloy.

Properties—Typical properties of this alloy in the various tempers are given in Tables I and II.

Table I
Typical Mechanical Properties of Aluminum-Silicon-Magnesium Alloy 51S

Temper	Tensile Strength, Psi.	Yield Strength ¹ , Psi.	Elongation, % in 2 in.	Shear Strength ² , Psi.	Brinell Hardness 10mm., 500kg.
O	16,000	6,000	30	11,000	28
W	35,000	20,000	24	24,000	64
T	48,000	40,000	14	30,000	95

¹Stress which produces a permanent set of 0.2% of the initial gage length.

²Single shear strength values from double shear tests.

Table II
Physical Properties of Wrought Aluminum-Silicon-Magnesium Alloy

	51SO	51SW
Sp.gr.	2.69	2.69
Density, lb. per cu.in.	0.097	0.097
Electrical conductivity, % of International Annealed Copper Standard	55	45
Thermal conductivity at 100°C cgs. units.	0.50	0.40
Coefficient of thermal expansion, average, 68-212°F.	0.0000130	0.0000130
Modulus of elasticity, psi.	10,300,000	10,300,000
Endurance limit psi., 500,000,000 cycles.	6,500	10,500

Corrosion Resistance—This alloy is resistant to corrosion under most atmospheric conditions. Under severe conditions of exposure paint protection is desirable.

Workability—In the annealed temper this alloy will withstand severe drawing and forming operations. After solution heat treatment (W temper) the alloy still has good workability and withstands all but the more severe drawing or forming operations. The fully heat treated temper (T) has decreased workability but, in many applications, forming can be carried out after solution heat treatment followed by aging of the formed part to the fully heat treated condition. Aging can be accomplished with little or no distortion.

Welding—This alloy can be welded using the methods employed for other aluminum alloys. The metal in the weld is in the cast condition and the effect of heat treatment is largely removed from the metal adjacent to the weld, consequently other forms of joining such as riveting are used where the maximum strength of the heat treated alloy is required.

Heat Treatment and Aging—Solution heat treatment of all forms of this alloy is carried out by heating at 960-980°F. in a fused nitrate bath or suitable air fur-

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†This alloy in the fully heat treated condition is covered by U. S. Patent 1,472,739.

nace. The time at this temperature depends upon the thickness of the section. After heating, the alloy is rapidly cooled to ordinary temperature with the minimum of delay, at most a few seconds, between removal from the heating medium and immersion in the quenching medium, usually cold water. This puts the alloy in the solution heat treated (W) temper.

Precipitation heat treatment or artificial aging is accomplished by reheating for 18 hr. at 315-325°F. Other aging treatments likewise at low temperatures are possible where special requirements are to be met. This operation, performed following solution heat treatment, puts the alloy in the fully heat treated (T) temper.

Annealing—Material which has not received any solution heat treatment can be completely annealed by heating to 640-670°F. and allowing to cool normally in the air. In certain forms of products, it is sometimes necessary to hold the alloy at the annealing temperature for 1 or 2 hr. to assure full annealing.

If the above mentioned annealing treatment is used on material which has been solution heat treated, a partial softening may occur and may be sufficient for some forming operations. The material, however, will not be dead soft. For complete annealing of these alloys which are in the heat treated temper, the metal should be heated for 2 hr. at a temperature of 750-800°F. and then slowly cooled to 500°F. at a rate not exceeding 50°F. per hr. The rate of cooling below 500°F. is not important.

Forms Produced—The alloy 51S is available in the form of sheet, plate, extruded shapes, tubing, and forgings.

Properties of Aluminum-Zinc Alloys

By L. W. Kempf*

General—In the early history of aluminum, zinc was considered one of the most important of the commercial hardening elements. There is, however, at present practically no commercial use of the binary aluminum-zinc alloys. A ternary alloy containing from 10-14% zinc with 2 or 3% copper is widely used in Europe for sand castings.^{1,2} In this country, also, a somewhat similar alloy with the zinc content restricted to 10 or 11% and copper to 2 or 3% with iron about 1.5% has until quite recently been produced in considerable tonnages as sand castings.^{3,4} The latter alloy is now being gradually replaced by heat treated alloys. Wrought aluminum-copper-zinc alloys have been used to some extent and there has been within the last few years an attempt to commercialize a wrought high strength alloy containing aluminum, zinc, and magnesium.⁵ Recently there has also been some commercial exploitation for forgings of a complex alloy containing about 10% zinc (Alloy 70S). There is not, however, any large production of wrought aluminum alloys containing zinc as the chief alloying ingredient.

Because of its high solubility in solid aluminum, zinc can be added in rather high percentages before encountering excessive brittleness. High tensile strengths are attainable in both cast and wrought products at relatively high percentages of zinc. There are disadvantages to the alloys containing more than about 10% zinc which more than offset the high strength and low metal cost. Among these disadvantages are high specific gravity, low strength at elevated temperatures, relatively poor casting qualities, relatively poor resistance to corrosion and, in some wrought products, a peculiar susceptibility to intercrystalline cracking under application of stress.

Properties of Castings—The tensile properties of some chill cast aluminum-zinc alloys according to Rosenhain and Archbutt⁶ are given in Fig. 1. It will be noted that the tensile strength increases continuously to about 40,000 psi. at 30% zinc.

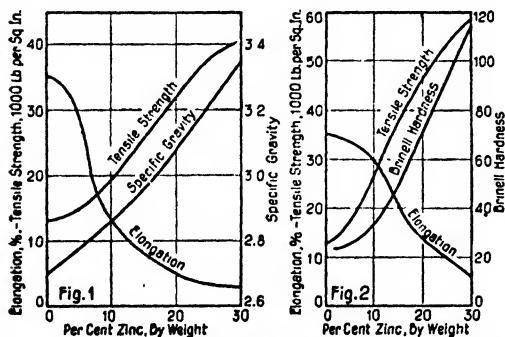


Fig. 1—Tensile properties of chill cast aluminum-zinc alloys.

Fig. 2—Effect of zinc on the tensile properties of aluminum (bars forged).

gravity of aluminum as rapidly as does copper, higher percentages of zinc are required to produce equivalent hardening effects, so the aluminum-zinc alloys as a class are the heaviest of the common aluminum-base alloys.

The aluminum-zinc alloys are notoriously hot short. They are also quite subject to shrinkage until the zinc content becomes rather high. On the whole, the casting properties of the binary alloys are considered relatively poor. The addition of copper markedly improves the casting characteristics as evidenced by the wide use in Europe of the casting alloy containing about 11% zinc and 3% copper.

Tensile Properties of Wrought Alloys—Fig. 2 shows the effect of zinc content on the tensile properties of aluminum in the form of forged bars. 4 in. square ingots were reduced at 700-800°F. to ¾ in. square rod from which standard ½ in.

Tensile property curves of sand castings will generally parallel the curves of Fig. 1 with slightly lower values for any specific zinc content. The elongation of sand castings approaches zero above about 15% zinc. Chill castings age harden to a marked, and sand castings to a somewhat lesser, extent on standing at room temperature. The elongation for alloys containing more than about 15% zinc becomes very low after a few months time. The tensile strength is correspondingly increased.

A curve is also included in Fig. 1 depicting the variation in specific gravity of the resulting alloys with increasing zinc contents. Although zinc does not increase the specific

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dia. specimens were machined. The specimens were heated 1 hr. at 880°F., quenched in water and aged 8 days at room temperature. The uniform increase in tensile strength and decrease in elongation with increasing zinc content is typical of the variation in properties of a solid solution with variation in concentration of the solute.

Up to about 12% zinc the alloys forge with considerable ease, but above this concentration their susceptibility to hot shortness renders them quite difficult to handle under the hammer. Similar observations regarding hot working properties have been made during hot rolling of alloys containing upwards of about 10% zinc. The forged alloys also exhibit spontaneous age hardening at room temperature after cooling in the air from the forging temperature.

Stress Cracking—Wrought products of aluminum-zinc alloys containing zinc concentrations higher than about 10% are susceptible to cracking or failure under the prolonged action of stresses well below the normal tensile strength. This phenomenon was encountered in the investigations of the National Physical Laboratory⁶ on alloys with zinc contents in the neighborhood of 20%. It was found that certain alloy additions, such as manganese, markedly decrease the tendency of the alloy toward this type of failure. Stress cracking can apparently be overcome by careful selection of alloy composition and control of the manufacturing processes.

Corrosion Resistance—The corrosion resistance of the aluminum-zinc alloys is generally considered to be inferior to that of the aluminum-copper or aluminum-silicon alloys. This is probably true in the alloys of such zinc concentrations that precipitation occurs at room temperature. It has been definitely shown that such precipitation decreases the corrosion resistance but also that the inherent corrosion resistance of the solid solution is not markedly inferior to that of the aluminum-copper alloys.

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Polishing of Aluminum for Metallographic Examination

E. H. Dix, Jr.,* and F. Keller*

General—The method of preparing metallographic specimens of aluminum alloys is similar to that employed for other metals, although a slightly different technique is required because aluminum alloys are relatively soft and are more readily flowed or scratched.

Full size specimens can be employed for macroscopic examination if they are not too large. Generally, it is necessary to cut small specimens of convenient size for both macroscopic and microscopic examination. These can be obtained by drilling, sawing, or shearing, but care should be taken to avoid overheating of the specimen or alteration of the structure in any manner. Before proceeding with the preparation of a specimen all oil, grease, dirt or other foreign materials should be removed.

Specimens too small to be handled conveniently during polishing should be mounted. The mounting of such specimens can be accomplished in one of several ways. For instance, with samples of sheet, a pack can be made by binding a number of pieces together by means of machine screws. In making up such a composite specimen of sheet or foil the pieces assembled in the pack are sometimes separated by fillerpieces of a similar alloy. The pack should be clamped tightly in order to minimize capillary retention and subsequent exudation of the etching solutions from crevices. Where the specimen is small or irregular in shape, it is general practice to embed the specimen in a mounting medium. The most economical and convenient method consists in placing the specimen in a ring of aluminum tubing and then filling the ring with melted sulphur. Sulphur does not chip readily during polishing, nor is it affected by the etching reagents commonly used. Other mounting materials, such as sealing wax, dental cements, and fusible alloys, also may be employed. If a suitable press is available, Bakelite and some of the transparent or semitransparent plastic materials such as Lucite, Cibacite, Resiglass or Tenite may be used. Any mounting material that may induce galvanic attack during etching or that is severely attacked by etching solutions should be avoided.

Since the objects of macroscopic and microscopic examinations are different, some variations in the polishing procedure are necessary. The following methods of preparation are recommended.

Preparation for Macroscopic Examination—Large specimens can be prepared satisfactorily for macroscopic examination by machining the surface in a lathe or shaper in accordance with the recommended practice for machining aluminum.¹ Smaller specimens are first smoothed on a sharp, medium mill file or microtome. Further preparation consists in rubbing the surface on several successively finer grades of abrasive cloth or paper, beginning with No. 180 Alloxite or a similar grade and finishing with No. 0 grade emery. The papers should be coated with a solution of paraffin in kerosene and should be backed by a piece of plate glass. This grinding should be carried out so that the cut being taken on a given paper is at right angles to that taken on the preceding paper.

Preparation for Microscopic Examination—The following procedure² is recommended for the preparation of specimens for microscopic examination:

1. A plane surface is obtained in the same manner as described for macroscopic examination.
2. The specimen is then rubbed successively on No. 0, 00, and 000 metallographic emery papers, coated with a solution of paraffin in kerosene to keep the specimen bright and prevent particles of abrasive from becoming embedded in the surface.

When a microtome³ of sufficient rigidity is available it can be used to replace operations 1 and 2 and will frequently give better results. The microtome blade should be kept well sharpened at all times and should be set to remove only a thin layer of metal in each cut.

3. The first wet polishing operation is carried out on a broadcloth pad mounted on a disc rotating at about 300 r.p.m. and using No. 600 alundum or a similar material as the abrasive. A quantity of the abrasive is placed in a flask with water

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and shaken until it is in suspension. In this way the mixture can be conveniently supplied to the pad while the specimen is being polished. The suspension should be allowed to settle as polishing progresses so that successive applications to the pad will carry progressively finer particles. The pad should finally be washed free of the coarser particles by means of a stream of water from a wash bottle and the polishing with this abrasive completed using a suspension from which all of the coarse particles have settled.

4. Final polishing is done on kitten's ear broadcloth mounted on discs rotating at about 150-200 r.p.m. The pad should be moistened with distilled water (not tap water) and a small quantity of heavy magnesium oxide worked into it with the palm of the hand; gritty particles and excess oxide are brushed off. The pad should be kept moist during the polishing operation by adding distilled water from a wash bottle as needed. The polishing should be continued until all striations from the alundum cut (operation 3) are removed; to avoid surface flow the specimen should frequently be lifted from the pad and turned through 180°. As this operation approaches completion, the pad should be washed nearly free of abrasive and the specimen held on the slowly rotating pad using a plentiful supply of water. In order to secure a really good polish, the finishing of this operation must be carried out carefully. The pressure and time required depend upon the composition and temper of the specimen being prepared.

When a satisfactory polish has been secured the specimen should be washed in a stream of warm tap water and dried by blowing the excess water from the surface. Touching or rubbing the surface on anything during or after the final polishing operation must be carefully avoided.

After polishing the specimens will retain their finish indefinitely if kept in a place where dirt from the atmosphere cannot collect on the surface. A desiccator or a sterilizer cabinet makes an excellent storage place.

There are several precautions which must be taken in order to secure satisfactory results from the wet polishing operations. For instance, there are several grades of magnesium oxide prepared specifically for metallographic use and successfully employed for polishing other metals. Many of these products, however, contain caustic and produce an etching effect on aluminum and so should not be used. It is also essential that distilled water be used in the wet polishing as tap water results in the formation of hard carbonate particles which may cause deep scratches. Finally, new polishing cloths should be boiled for several hours before being used in order to soften the fibers and, when not in use, should be kept moist with distilled water acidified with HCl.

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Etching Aluminum For Metallographic Examination

By E. H. Dix, Jr.* and F. Keller*

General—Metallographic specimens are etched in order to remove flowed metal from the polished surface, and to aid, by coloring or attacking constituents and phases, in revealing the microstructure. The type of etching solution required varies with the magnification to be used in subsequent examination, as well as with the purpose for which the etching solution is being employed.

Etching for Macroscopic Examination—Etching by totally immersing the specimen in the etching reagent produces the best results for macroscopic examination; however, for large sections it is often more convenient to apply the etching reagent to the surface by means of a soft cotton swab. This latter method is satisfactory provided that the etching reagent is applied uniformly to the surface. All oil or grease should be removed from the specimen before etching, otherwise the etching action will not be uniform.

Four types of etching solution are in general use for macroscopic etches. These consist of various concentrations of (1) sodium hydroxide, (2) hydrofluoric acid, (3) mixtures of hydrofluoric and hydrochloric acid, or (4) hydrofluoric, hydrochloric, and nitric acid. The HF-HCl acid mixture (No. 7, Table I), and the HF-HCl-HNO₃ acid mixture (No. 8, Table I), give the best results. When reagent No. 7 is used the specimen should be subsequently immersed in, or swabbed with concentrated HNO₃ to remove the etching products and to improve the grain contrast. Acid mixture No. 8 requires no subsequent treatment with HNO₃.

Etching for Microscopic Examination—Six etching solutions are recommended for general use in connection with microscopic examination. These are all aqueous solutions made up by volume when acids are used and by weight in the case of sodium hydroxide. They are designated No. 1-6 in Table I.†

The most generally useful etch is that of swabbing with 0.5% hydrofluoric acid for 15 sec. This satisfactorily removes surface flow, reveals any minute particles of constituents and also offers some possibilities for the identification of constituents. The other reagents are employed for specific purposes such as definite identification or for revealing grain structure of certain alloy types.

Specimens may be etched by immersion in the solution or by swabbing with a soft absorbent cotton swab moistened with the reagent. The latter method gives uniform and satisfactory results and is especially desirable in preparing a surface for photography. It is important to control the temperature of the specimen and of the reagent, the concentration of the reagent, and the time of etching. When the immersion method is employed the specimen should not be held in the solution with tongs, since these are usually of a different alloy than the specimen and produce electrolytic effects.

The Identification of Constituents—The identification of constituents is best accomplished at a magnification of 500 diameters or higher; therefore a 4 mm. objective with a 10X ocular is generally satisfactory. The first attempt to identify constituents should be made on the unetched specimen using color and manner of occurrence as a means of differentiation. For judging color the illumination should be approximately that of daylight quality. Eastman filter No. 78A converts the light of a 5 ampere carbon arc with Eastman neutral tint filter to approximately that of daylight. Any white light is satisfactory although the bluish tints aid in the separation of different constituents.

The characteristics of the principal constituents in commercial aluminum alloys as polished and after using the etching reagents previously described are given in Table II. A systematic guide for the identification of constituents similar to the one suggested by Dix and Keith¹⁷ with additions²⁸ is given in Table III. This guide is subject to the limitations of any etching procedure; but it should prove adequate as a means of identification even though the composition of the alloy is unknown.

The etching characteristics of the various constituents were obtained from a set of standard specimens prepared from high purity aluminum (99.95%) to which only the purest alloying elements were added. In these alloys the characteristic

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†Tables I, II, and III are given at end of article.

constituents occur without the presence of others that usually arise from the impurities existing in commercial ingots and alloys. For those interested in identifying constituents in aluminum alloys such a set of standards is invaluable.

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Table I
Etching Solutions

Etching Reagent	Concentration	Specific Use	Remarks
1. Hydrofluoric acid	HF conc. 0.5 ml. H ₂ O 99.5 ml.	General, microscopic	Swab with soft cotton swab for 15 sec.
2. Sodium hydroxide	NaOH 1 g. H ₂ O 99 ml.	General, microscopic	Swab for 10 sec.
3. Sodium hydroxide	NaOH 10 g. H ₂ O 90 ml.	Microscopic	Immerse 5 sec. at 70°C., rinse in cold water
4. Sulphuric acid	H ₂ SO ₄ conc. 20 ml. H ₂ O 80 ml.	Separates Al-Cu-Fe-Mn from Al-Fe-Mn or αAl-Cu-Fe	Immerse 30 sec. at 70°C., quench in cold water
5. Nitric acid	HNO ₃ conc. 25 ml. H ₂ O 75 ml.	αAl-Fe-Si from FeAl ₃ microscopic	Immerse for 40 sec. at 70°C., quench in cold water
6. Keller's etch	HF conc. 1.0 ml. HCl conc. 1.5 ml. HNO ₃ conc. 2.5 ml. H ₂ O 95.0 ml.	Microstructure of duralumin type alloys	Immerse for 10-20 sec., wash in stream of warm water
7. Flick's etch	HF conc. 10 ml. HCl conc. 15 ml. H ₂ O 90 ml.	Macroscopic	Immerse for 10-20 sec., wash in warm water followed by dip in conc. HNO ₃
8. Tucker's etch	HF conc. 15 ml. HCl conc. 45 ml. HNO ₃ conc. 15 ml. H ₂ O 25 ml.	Macroscopic	Etch by immersion
9. Vilella's etch	HF conc. 2 pt. HNO ₃ conc. 1 pt. Glycerine 3 pt.	General	Etch by immersion

(Continued)

Table II
Etching Characteristics of Constituents in Aluminum Alloys

Constituent	Reagent		
	0.5% HF, swab for 15 sec., wash in cold water	1% NaOH, swab for 10 sec., wash in running water	20% H ₂ SO ₄ at 70°C., immerse specimen for 30 sec., quench in cold water
Silicon	Outlined. Unattacked. Color lightened.	Outlined. Unattacked. Color slightly lightened.	Unattacked. Color lightened.
Mg ₂ Si	Colored bright blue.	Outlined. Color Unchanged.	Action violent. Some particles dissolved, any left have a blue color.
CuAl ₂	Outlined. Part of pinkish tinge removed. Constituent light and clear.	Outlined. Part of pinkish tinge removed. Constituent light and clear.	Outlined. Part of pinkish tinge removed. Constituent light and clear.
α Al-Mg ..	Outlined. Slightly clearer and more watery. Black pits appear in particles.	Not Outlined. Unattacked. Uncolored.	Attacked vigorously, resulting in pitting. Some particles dissolved.
FeAl ₃ ..	Slightly darkened. Brown stains appear on large primary particles.	Outlined. Slightly darkened.	Heavily attacked. Particles often dissolved or deeply pitted. Color darkened.
α Al-Fe-Si	Outlined. Not colored.	Outlined. Not colored.	Outlined. Blackened and attacked
β Al-Fe-Si	Blackened and attacked.	Outlined. Uncolored. Unattacked.	Outlined. Slightly darkened and pitted.
Al-Mn	Outlined. Slightly darkened.	Attacked. Colored brownish or bluish but coloring is uneven.	Outlined. Uncolored Unattacked.
NiAl ₃ ..	Outlined. Colored blue and brown.	Outlined. Darkened slightly. Not colored.	Outlined. Darkened slightly. Not colored.
Al-Fe-Mn ..	Outlined. Colored brown. (Sometimes bluish.)	Outlined. Particles pitted. (Often a rough blue color on a few particles)	Outlined. Unattacked Uncolored.
Al-Cu-Ni	Outlined. Unattacked. Darkened.	Outlined. Slightly darkened. Not attacked.	Outlined. Slightly darkened. Not attacked.
α Al-Cu-Fe ..	Outlined. Blackened.	Outlined. Unattacked. Uncolored.	Outlined. Unattacked. Uncolored.
β Al-Cu-Fe ...	Outlined. Unattacked Uncolored.	Outlined. Slightly darkened.	Outlined and uncolored. Often show black cores which are probably FeAl ₃ .
Al-Cu-Fe-Mn...	Outlined. Colored light brown to black. Usually appears roughened.	Outlined. Uncolored.	Outlined. Blackened.
Al-Mn-Si	Outlined. Colored light brown to black. Usually appears roughened.	Outlined. Usually appears rough and attacked. Slightly darkened.	Outlined. Appears rough and attacked. Darkened slightly.
Al-Cu-Mg	Outlined. Blackened.	Outlined. Colored light brown.	Outlined. Attacked. Blackened.
CaSi ₂	Colored blue. Heavily outlined.	Outlined. Color unchanged.	Outlined. Colored blue. Roughened.
Al-Cu-Mn	Outlined. Attacked. Blackened.	Outlined. Unattacked. Uncolored.	Outlined. Colored light brown.
CrAl ₃	Outlined. Unattacked. Uncolored.	Outlined. Unattacked. Uncolored.	Outlined. Unattacked. Uncolored.
Al-Cr-Fe	Colored light brown. Unattacked.	Not outlined. Unattacked. Uncolored.	Outlined. Unattacked. Uncolored.

(Continued)

Table II—Continued
Etching Characteristics of Constituents in Aluminum Alloys

Constituent	Reagent		
	25% HNO ₃ at 70°C., immerse specimen for 40 sec., quench in cold water	10% NaOH at 70°C., immerse specimen for 5 sec., rinse in cold water	0.5% HF, 1.5% HCl, 2.5% HNO ₃ , immerse specimen for 15 sec., rinse in warm water
Silicon	Outlined. Unattacked. Color lightened.	Outlined. Unattacked. Color lightened.	Outlined. Unattacked. Color lightened.
Mg ₂ Si	Colored brown or black.	Outlined. Color light- ened.	Outlined. Colored blue to brown.
CuAl ₂	Colored brown or black.	Pitted. Colored light to dark brown.	Outlined. Constituent light and clear.
α Al-Mg	Heavy attack, parti- cles grayish and watery.	Outlined. Unattacked. Uncolored.	Heavily outlined. At- tacked by pitting.
FeAl ₃	Outlined. Contrast with Al-Fe-Si im- proved.	Outlined. Colored deep brown.	Outlined. Uncolored. Slightly attacked.
α Al-Fe-Si	Outlined. Contrast with FeAl ₃ im- proved.	Attacked. Blackened	Heavily outlined. Darkened and roughened.
β Al-Fe-Si	Outlined. Uncolored. Unattacked.	Outlined. Slightly darkened and at- tacked.	Outlined. Slightly darkened and roughened.
Al-Mn	Not outlined. Unat- tacked. Uncolored.	Colored blue or brown.	Outlined. Unattacked. Uncolored.
NiAl ₃	Outlined. Uncolored. Unattacked.	Colored blue to deep brown.	Colored brown to black.
Al-Fe-Mn	Outlined. Unattacked. Uncolored.	Colored deep brown to blue.	Outlined. Attacked. Darkened.
Al-Cu-Ni	Blackened. Some parti- cles dissolved.	Outlined. Unattacked. Uncolored.	Outlined. Some large particles stained unevenly.
α Al-Cu-Fe	Outlined. Unattacked. Uncolored.	Outlined. Blackened. Attacked.	Blackened.
β Al-Cu-Fe	Outlined. Slightly darkened and at- tacked.	Pitted. Colored light brown.	Outlined. Blackened.
Al-Cu-Fe-Mn	Outlined. Unattacked. Uncolored.	Outlined. Uncolored.	Outlined. Colored brown to black.
Al-Mn-Si	Outlined. Appears rough. Darkened slightly.	Outlined. Attacked. Color not changed.	Outlined. Slightly darkened.
Al-Cu-Mg	Outlined. Attacked. Blackened.	Outlined. Unattacked. Colored brown.	Colored brown to black.
CaSi ₂	Outlined. Unattacked. Uncolored.	Outlined. Blackened. Attacked and roughened.	Colored brown to blue. Mottled.
Al-Cu-Mn	Outlined. Unattacked. Uncolored.	Outlined. Attacked. Blackened.	Attacked. Blackened.
CrAl ₃	Outlined. Unattacked. Uncolored.	Outlined. Colored blue to brown un- evenly.	Outlined. Unattacked. Uncolored.
Al-Cr-Fe	Not outlined. Unat- tacked. Uncolored.	Small particles col- ored brown to black. Large parti- cles, stained all colors.	Outlined. Colored light brown. Not at- tacked.

Hardeners for Aluminum

By H. O. Burrows*

Alloying elements are commonly added to aluminum in the form of rich alloys containing aluminum and relatively large amounts of the alloying elements. They are usually made in one or two ways: (1) By melting both the aluminum and the element to be alloyed and mixing them in the molten condition; or (2) by melting the aluminum first, and when it has been heated to a relatively high temperature, adding the alloying element and stirring the mixture until the alloying element has been dissolved in the aluminum.

Rich alloys, which are brittle and broken readily into small pieces to obtain the desired amount, are usually cast in large ingots. Where the rich alloys are not easily broken, it is customary to cast them in small notched ingots.

Where the cooling characteristics of the rich alloys permit, a relatively uniform composition throughout the cross section of the ingot may be obtained. For example, alloys of aluminum with about 33-54% copper (the composition of the eutectic and the compound CuAl, respectively) solidify over a relatively narrow temperature range and are usually quite uniform in composition. Some other hardeners, particularly those of the hypereutectic composition, such as nickel-rich aluminum alloys and manganese-rich aluminum alloys, tend to segregate during solidification and care must be exercised in their use.

Aluminum-Copper Hardeners—The most common copper-rich aluminum alloy is one containing approximately 50% copper and 50% aluminum. The purity of the alloy will depend upon the purity of the metals used and the care exerted to avoid contamination during the alloying operation.

Various other copper-rich aluminum alloys, such as the 60-40 and 80-20 aluminum-copper alloys, are used for making additions of aluminum and copper to zinc in the manufacture of zinc-base die castings.

Composition Limits and Properties of Standard Aluminum-Copper Hardeners

	50-50 Al-Cu		60-40 Al-Cu		80-20 Al-Cu	
	Min.	Max.	Min.	Max.	Min.	Max.
	Per Cent		Per Cent		Per Cent	
Cu	49.00	51.00	39.00	41.00	19.00	21.00
Fe		0.75		0.50		0.50
Si		0.60		0.50		0.50
Zn		0.20		0.30		0.30
Mn		0.10		0.05		0.10
Mg		0.10		0.05		0.05
Ni		0.10		0.10		0.05
Pb				0.01		0.01
Sn				0.01		0.01
Cd				0.01		0.01
Al	Remainder		Remainder		Remainder	
Melting range	1010-1090°F.		1010-1050°F.		1010-1095°F.	
Brittle	Yes		Yes		No	
Tendency to segregate	Slight		Slight		Slight	
Usual size ingot	20-40 lb.		Small notched		Small notched	

Aluminum-Silicon Hardeners—The aluminum-silicon-rich alloys are used to add silicon to aluminum or to the various aluminum alloys.

Composition Limits and Properties of Standard Aluminum-Silicon Hardeners

	85-15 Al-Si		70-30 Al-Si	
	Min.	Max.	Min.	Max.
	Per Cent		Per Cent	
Si	10.00	15.00	27.00	32.00
Cu		0.20		0.30
Fe		0.75		1.00
Mg		0.03		0.10
Mn		0.03		0.10
Al	Remainder		Remainder	
Melting range	1070°F. 1070-1165°F.		1070-1510°F.	
Brittle	No		No	
Tendency to segregate	Slight		Decided	
Usual ingot size	Small notched		Small notched	

*Castings Division, Aluminum Co. of America, Cleveland.

Aluminum-Nickel and Aluminum-Manganese Hardeners—Since nickel in concentrations higher than 6% and manganese in concentrations higher than 2% raise the melting point of aluminum rapidly, nickel-rich aluminum alloys and manganese-rich aluminum alloys are generally made with concentrations of nickel and manganese not exceeding 10%. Occasionally a 25% nickel-rich aluminum alloy is employed.

Composition Limits and Properties of Standard Aluminum-Nickel Hardeners

	90-10 Al-Ni		75-25 Al-Ni	
	Min.	Max.	Min.	Max.
	Per Cent		Per Cent	
Ni	9.00	11.00	20.00	25.00
Mn		0.10		0.20
Cu		0.30		0.30
Fe		0.75		1.00
Si		0.50		0.50
Al	Remainder		Remainder	
Melting range	1185-1305°F.		1185-1720°F.	
Brittle	No		Slightly	
Tendency to segregate	Considerable		Decided	
Usual ingot size	Small notched		Small notched	

Composition Limits and Properties of Standard Aluminum-Manganese Hardener

	90-10 Al-Mn	
	Min.	Max.
	Per Cent	
Cu		0.50
Fe		1.00
Si		0.50
Mn	5.00	10.00
Mg		0.50
Al	Remainder	
Melting range	1217-1335°F. 1217-1475°F.	
Brittle	No	
Tendency to segregate	Decided	
Usual ingot size	Small notched	

Aluminum-Copper-Zinc Hardeners—For zinc-base die casting alloys in which both aluminum and copper are employed, the alloying elements are added by means of a rich alloy containing aluminum, copper, and zinc. Zinc is present in the rich alloy to lower its melting point and thus facilitate alloying with metallic zinc.

Composition Limits and Properties of Typical Aluminum-Copper-Zinc Hardener

	31 Cu 15 Zn 54 Al	
	Min.	Max.
	Per Cent	
Cu	30.00	31.00
Zn	14.50	15.50
Fe		0.50
Si		0.50
Mn		0.10
Pb		0.01
Sn		0.01
Cd		0.01
Al	Balance	
Brittle	Slightly	
Tendency to segregate	Slight	
Usual ingot size	Small notched	

Aluminum-Zinc Hardeners—For zinc-base die casting alloys containing only aluminum, the alloying element is added in the form of a hardener composed of approximately 40% aluminum and 60% zinc. Only high purity materials may be employed in its manufacture.

Composition Limits and Properties of Aluminum-Zinc Hardeners

	40 Al Min. Per Cent	60 Zn Max.
Al	39.00	41.00
Cu		0.20
Fe		0.40
Si		0.25
Sn		0.01
Pb		0.01
Cd		0.01
Zn	Remainder	
Melting range	840°-990°F.	
Brittle	Slightly	
Tendency to segregate	Slight	
Usual ingot size	Small notched	

Aluminum-Iron Hardeners—For certain types of casting alloys, the presence of about 1.25% iron is desirable as it is reported to increase the hardness and wear resistance of the alloy and decrease the tendency toward hot shortness. For these alloys, iron may be introduced into the mixture by means of an aluminum-iron alloy containing between 5 and 10% iron.

The valuable properties of aluminum-bronze have been known for many years but one of the principal problems in producing good aluminum-bronze is getting the iron into solution. It has been found that iron may be introduced uniformly into the mixture through the use of an aluminum alloy containing approximately 90% aluminum and 10% iron.

Composition Limits and Properties of Aluminum-Iron Hardeners

	90-10 Al-Fe Min. Max. Per Cent		50-50 Al-Fe Min. Max. Per Cent		Min.	20-80 Al-Fe Per Cent		Max.
Cu		0.50		1.00				0.50
Fe	5.00	10.00	45.00	55.00	70.00			80.00
Si		0.50		1.00				1.00
Mn		0.10		0.75				0.75
Al	Remainder		Remainder			Remainder		
Melting range	1210-1400°F. 1210-1625°F		2140-2230°F.			2320-2480°F 2480-2580°F.		
Brittle	No		Yes			No		
Tendency to segregate	Considerable		Slight			Slight		
Usual mold size	Small notched		20-40 lb.			20-40 lb.		

Temperature Measurements in Molten Aluminum and Its Alloys

By Kirtland Marsh*

Type of Pyrometer—A thermoelectric pyrometer provides the most satisfactory means for determining the temperature of molten aluminum. The subject of thermoelectric pyrometers has been discussed in other sections of this Handbook, so only those phases of the subject pertaining particularly to the measurement of the temperature of molten aluminum will be discussed.

Cold Junctions—Since close temperature control is desirable ($\pm 20^{\circ}\text{F.}$ in the melting operation and $\pm 10^{\circ}\text{F.}$ in the pouring operation), provision should be made for maintaining a constant cold junction temperature for all thermocouples, or means must be provided to compensate for fluctuating cold junction temperatures. This is easily accomplished and is mentioned only because it is a requirement which is too often neglected altogether, or only partially met. Fluctuation of the cold junction temperature of a base metal thermocouple will produce errors in the temperature reading of about the same magnitude as the fluctuation of the cold junction temperature.

Thermocouple Protection Tubes—Every base metal thermocouple in common use is readily attacked by molten aluminum, some to a greater extent than others, but all to a sufficient extent to warrant the use of a suitable protection tube over the thermocouple wherever practicable. A thermocouple actually measures the temperature of its hot junction, so the protection tube and the hot junction must become the same temperature as the material before a correct reading can be obtained. A protection tube over a thermocouple materially increases the time required to secure a correct temperature reading. In the case of a melting furnace, the thermocouple and protection tube can be immersed as soon as the aluminum is melted down and allowed to remain in the metal at least until it is ready to be poured, so that the 5 min. or more required for the protection tube and thermocouple to reach the temperature of the molten metal is not a handicap. However, when it is desired to measure the temperature of the metal in a pouring ladle, time is an important factor and an unprotected couple is generally preferred.

Protection tubes are made preferably of grey cast iron. They are inexpensive and more resistant to attack by molten aluminum than other alloys which have been tried such as steel, wrought iron, or heat resisting steel. Even the cast iron will not satisfactorily resist molten aluminum unless given suitable protective coatings.

Protective Coatings for Tubes—A simple and inexpensive method of preventing the molten aluminum from dissolving or alloying with the protection tube consists of applying a wash made of hydrated lime or an aluminum pigment and an equal volume of water. The wash can be easily applied by a brush, particularly if the tube is heated to a temperature under the boiling point of water ($180\text{--}200^{\circ}\text{F.}$). Another method is to dip the heated protection tube once into the wash and quickly withdraw it before the tube is sufficiently chilled to prevent the rapid drying of the wash.

If the thermocouple is for use in an open top melting pot and is suspended from a point above the pot, the above wash is very effective, but if the thermocouple is mounted in such a manner that the protection tube is subject to contact with solid objects, the wash will be easily abraded or knocked off. In such cases, a protective coating much more resistant to abrasion can be made by mixing the lime with a solution consisting of 25% by volume of commercial sodium silicate and 75% water. This wash can be applied in the same manner as the lime and water wash, but the sodium silicate content should not be allowed to increase more than a few per cent by evaporation of the water, or a spongy and less satisfactory coating will result.

Protection tubes should be recoated as often as necessary to maintain an effective coating. Before a tube is recoated, it should be carefully cleaned to remove any aluminum which may cling to it, and also any previous coating which may have become loosened. Occasionally the entire tube should be scraped clean to remove any previous coat and any loose iron oxide scale, since a thick coat of

*U. S. Aluminum Co., New Kensington, Pa.

lime or loose scale will readily crack off while the tube is being heated up in the molten metal. The lime wash is much more adherent to a new cast iron protection tube which has been exposed to atmospheric influence long enough to become rusted, than to a smooth unrusted casting. The rusting should not be allowed to progress far enough to produce a loose scale.

Thermocouple Holder—A large proportion of aluminum is melted in open-top melting pots. It is generally a simple matter to suspend a thermocouple over the pot so that it may be lowered into the metal or raised out of the way as required. A satisfactory protection tube and holder for open-pot melting furnaces are shown in Fig. 1. The holder may be suspended by means of a chain attached by screws at each end. The tube is readily removed from the holder so that replacement is simple.

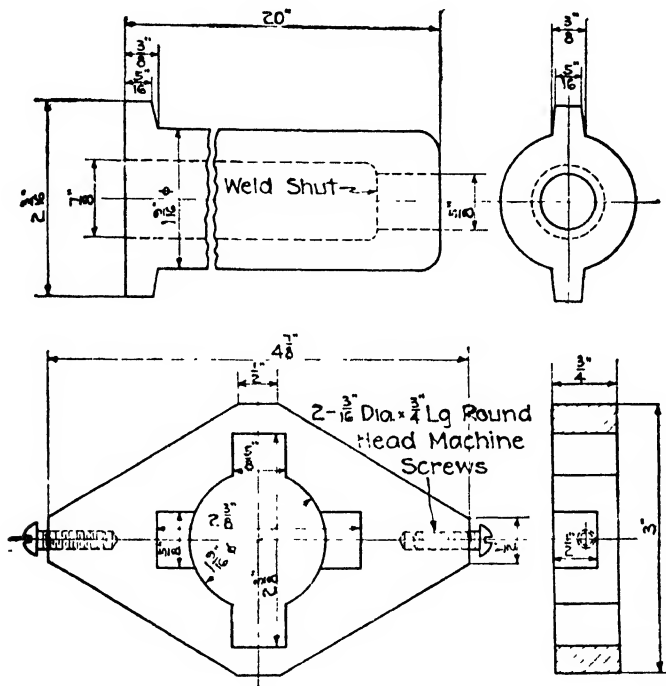


Fig. 1—Protection tube and holder for thermocouple. This tube may be cast with a solid end or welded shut as indicated.

Thermocouples—The measurement of the temperature of molten aluminum in pouring ladles must be accomplished easily and quickly so that the use of a thermocouple in a heavy protection tube is out of the question. Furthermore, many thermocouples themselves are sufficiently massive to require an appreciable length of time to attain temperature equilibrium in a bath of molten aluminum.

The most common form of thermocouple consists of two wires of different chemical composition welded together at one end to form the hot junction. The temperature actually measured is the temperature of the hot junction. The correct temperature of the molten aluminum is, therefore, not obtained until the thermocouple has been in the molten metal long enough for the hot junction to reach the temperature of the molten metal. If, however, the two wires are not welded, the molten aluminum will complete the electrical circuit and the true temperature of the molten metal will be indicated in a much shorter time than in the case of a welded thermocouple made of wires of the same size or mass.

A quick reading thermocouple can be made of No. 8 B. & S. gage chromel and alumei thermocouple wires. Both wires should be insulated with asbestos to within $\frac{1}{4}$ – $\frac{1}{2}$ in. of the end, otherwise the hot junction between the two wires may be formed at the surface of the molten aluminum. With the elements insulated, the

hot junction will be at or close to the ends of the elements, so the temperature at any depth in the pouring ladle can be obtained by immersing the couple to that depth.

Thermocouple Insulations—Not all types of asbestos insulation are satisfactory. The best form is a continuous felted layer of asbestos on each wire. This can be obtained from the pyrometer manufacturers.

The felted asbestos will become brittle and rub off, but with reasonable care the wear on the asbestos insulation will about equal the erosion of the wires. If the insulation wears away faster than the wires are dissolved, the bare wire should be cut off to within $\frac{1}{4}$ in. of the insulation, so that the hot junction, formed by the molten metal, is well below the surface.

Cleaning Thermocouples—Most of the molten aluminum which may adhere to the thermocouple when it is withdrawn should be shaken off before the aluminum solidifies; otherwise the next time the couple is used a much longer time will be required to obtain a true temperature reading.

The thermocouple should never be whipped against any solid object to remove the molten aluminum, because that would break off the insulation. To remove the aluminum, move the couple rapidly in a direction parallel to its length and then suddenly stop it, in a manner similar to shaking ink from a fountain pen.

Checking Pyrometers—The best pyrometers must be checked occasionally and they should be checked or calibrated at about the same temperature for which they are used. Because of the definite freezing or arrest points of pure aluminum and its alloys, it is a simple matter to calibrate the pyrometers in an aluminum foundry, as follows:

Fill a small crucible or pouring ladle with molten pure aluminum or one of the alloys shown in Table I, and immerse the thermocouple to a depth of 6-8 in. in the molten metal. While gently stirring the molten metal with the thermocouple or a stirring rod, read the temperature as indicated by the instrument at $\frac{1}{2}$ min. intervals. The temperature will drop at a relatively uniform rate until the freezing point of the metal is reached, when the drop in temperature will cease or become much reduced until the metal is entirely solidified. The temperatures given in Table I apply only to the beginning of the arrest period or to the point at which the direction of the time-temperature curve changes. If the mass of molten metal were great enough and it were vigorously stirred there would be a period during which the temperature would not change, but in practice there is generally only a change in the slope of the time-temperature curve. Enough metal should be used, stirring should be sufficiently vigorous, and the depth of immersion of the thermocouple in the molten aluminum should be great enough so that the change in slope of the curve will be sharp and well defined, rather than gradual or rounded off. No. 12 alloy does not give as sharp a change in slope as pure aluminum or the other alloys mentioned, but can be used if no other metal is available. The temperature as indicated by the pyrometer should agree with the temperature as given in the table, at the beginning of the arrest period, but if it does not the pyrometer is in error by an amount equal to the difference between the true temperature and the temperature as indicated.

Although a pyrometer in an aluminum foundry is not ordinarily used at temperatures as low as the freezing point of aluminum, the temperature at which it is used is sufficiently close to the freezing temperature that the error will be about the same.

In order to obtain a definite arrest point, the metal in the crucible should be stirred continuously by moving the couple back and forth. A heavy protection tube cannot be used over the couple, for this would almost entirely obliterate the arrest point on the time-temperature curve. The quick reading couple can be immersed directly in the molten aluminum, and the welded couples used in protection tubes in the melting pots can be immersed in the same manner if they are first given a protective coating of lime wash. The coating should be perfectly dry before the couple is immersed, and the coating must not be rubbed off while the couple is in the metal.

Not all alloys of aluminum have a sufficiently definite arrest period during solidification to make them suitable for freezing point calibrations. Furthermore, since the arrest period occurs at different temperatures for different alloys, the

metal selected must be of known composition or the freezing temperature must be determined experimentally with a pyrometer of known accuracy. It is generally possible to secure enough new metal, either commercially pure aluminum or one of the alloys mentioned in the table, for a freezing point determination.

It is not necessary to allow the metal to completely solidify in making a freezing point determination, for with a reasonable amount of metal, the arrest period will extend over several minutes, and as soon as it is definitely reached, the couple may be withdrawn and the metal dumped out of the crucible before it becomes solid.

Table I
Freezing Points of Aluminum and Its Alloys

Al	Cu	Composition by %					Total im- max. purities	Alloy	Arrest Point, °F.
		Si	Zn, max.	Fe, max.	Mg	Mn, max.			
99.95	.....	.....	...	...	...	...	0.05	Pure Al	1220
99.2	.....	.....	...	...	...	...	0.8	Comm. pure Al	1216
67.0	33.0	.....	...	...	...	...	0.05	Al-Cu eutectic ¹	1018
67.0	33.0	.....	...	...	...	...	0.8	Al-Cu eutectic ²	1010
91.1-89.6	7.0-8.5	.....	0.2	...	...	...	1.7	No. 12	1160
86.15-85.15	0.15†	12.0-13.0	0.2	0.8	•	0.7	....	No. 47 not modified	1071

¹Made from pure (99.95%) aluminum.

²Made from commercially pure (99.2%) aluminum.

†Maximum.

•Trace.

If the zero setting of the instrument is properly maintained, any change in calibration would ordinarily be gradual unless due to accident, in which case the error would probably be large enough to be apparent without an actual calibration. In some large aluminum foundries, the quick reading couples for taking pouring temperatures are checked once a day. The writer recommends the calibration of all quick reading couples at least once a week, and of all others, at least once a month.

Aluminum Die Castings

By G. M. Rollason¹ and Sam Tour²

Introduction—In die casting aluminum a hydrostatic pressure, usually in the neighborhood of 400-500 psi., is applied to the molten metal to force it into and hold it in the cavity of a metallic mold or die until solidification takes place. The use of this applied pressure involves specialized equipment and results in a product rather sharply differentiated from that of any other casting process. For certain applications, where a somewhat higher cost is justified, a more massive type of die casting machine, using pressures of 2000 psi. and upwards, has been developed.

The special characteristics of die castings offer a number of economic benefits where a metallic piece or part is used in large quantities. The die casting process affords:

1. Means of producing pieces at an extremely rapid rate with uniformity of material, appearance, and dimension.
2. Reduction or total elimination of the necessity for machining operations because of dimensional accuracy, ability to cast threads and core holes.
3. Means of producing integral pieces of different kinds of metal by casting into position the studs, bushings, and inserts.
4. Production of castings with thin and light sections.
5. Parts formed by assembly of sheet metal or stampings can be produced in one die casting where the integral construction gives greater strength and rigidity at considerably lower cost per piece without the need for an expensive series of punching, forming, and drawing dies, and the necessary jigs and fixtures usually employed.
6. Smooth surfaces permitting low cost of finishing operations.
7. The accurate reproduction of engraved or ornamental designs.

The initial cost of aluminum alloy die castings is slightly more than that of other common white metal die castings. To offset this cost differential, aluminum alloy die castings offer the advantages of light weight, superior resistance to corrosion, resistance to the effect of moderately elevated temperature, much higher degree of permanency of dimension and shape, and superior electrical and thermal conductivity.

Based on these characteristics, aluminum die-castings have found commercial application in the manufacture of household utensils and appliances, including washing machines and vacuum cleaners; automobile parts, such as hydraulic brake pistons, brackets, housings, pumps, carburetor bodies, and hardware; airplane engine parts; outboard motors; portable tools; electrical equipment; cases and frames for instruments and meters; gas burners; binoculars; typewriter and business-machine parts; rubber molds.

Scope and Limitations—In designing or considering the use of die castings for a given purpose, the following general characteristics should serve as a guide, but in complicated, elaborate or doubtful cases, advantage should be taken of the experience of a die casting engineer.

Size—The principles of die design and construction used in commercial work have proven applicable to successively larger and larger pieces. Aluminum die castings have been produced weighing 19 lb. with overall dimensions 36 x 12 x 9 in. Dimensions in one direction may exceed these considerably, and castings have been made of over 40 in. in length. Castings 25 in. in length are quite common. The low limit on size of die casting depends on economy and dimensional accuracy. For very small work, stampings or screw machine products should be considered.

Section Thickness—On large aluminum die castings, metal thickness can be reduced to dimensions of 0.085-0.100 in. With sections of less than 6 in. in length or width, the metal thickness may run as low as 0.050-0.065 in. It is usually desirable in designing die castings to keep wall thickness fairly uniform or at least to avoid abrupt changes in thickness. It is also desirable to keep sections as light as possible, consistent with requirements of strength and rigidity.

Dimensional Accuracy—Commercial aluminum die castings are generally produced to tolerance limits of plus or minus 0.0015 in. per linear in. of dimensions. These limits are governed by the rules for shrinkage which are established

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by experience. When once the shrinkage of a particular casting has been determined by successive trial and re-working of the dies, much closer limits can be maintained on dimensions of 3 in. or more. Dimensions measured perpendicular to the parting line of a casting are maintained within limits of minus nothing plus 0.010 of an in. in the largest castings, down to minus nothing plus 0.003 of an in. on small pieces.

Die castings have been produced for special purposes in commercial quantities with limits of plus or minus 0.001 of an in. across the parting line, but such close tolerances are not general. Each individual job must be engineered with specific tolerances in mind.

Cores—The coring of required holes or cavities in a die casting, wherever possible, not only reduces machining operations, but saves metal weight and permits the beneficial chilling action of the steel cores to be exerted throughout a greater part of the casting. Slight drafts are used on the cores to permit their withdrawal without injury to core or casting.

Draft on Die Casting Cores

Approximate Dia. of Hole	Amount of Draft, per in. of Depth
Less than $\frac{1}{8}$ in.*.....	0.015-0.020 in. on dia.
$\frac{1}{8}$ -1 in.	0.010 in. on dia.
More than 1 in.....	0.010-0.030 in. on dia. (depending on size and design)

*Small holes for tapping are usually cast to root dia. of thread with standard draft added.

Standard drafts may be reduced where necessary, probably involving more frequent replacement of cores.

Alloys—The great bulk of aluminum alloys used in die castings fall into three main groups:

1. Aluminum-copper alloys.
2. Aluminum-silicon alloys.
3. Combinations of 1 and 2, that is, aluminum-copper-silicon alloys with or without further additions of nickel or other elements.

Aluminum-Copper Alloys—Copper is added to aluminum in amounts varying from 4-14% and occasionally higher. The constitution of aluminum-copper alloys is described elsewhere by Dix and Richardson in *National Metals Handbook*. The effect of increasing additions of copper is to render the resulting alloys progressively harder and less ductile. At the same time, increase in copper content lowers the melting point, increases fluidity, reduces shrinkage and thereby improves die casting properties up to the point where excessive hot shortness sets in, making it impossible to eject the casting from the die without breakage. Copper has a tendency to reduce the corrosion resistance of aluminum.

Aluminum-Silicon Alloys—Silicon is added in amounts varying from 5-13%. The effect of increasing additions of silicon to aluminum is a progressive hardening and improvement in casting properties. At the same time the corrosion resistance is maintained at a high level.

The ease of casting increases with greater additions of silicon up to the eutectic composition. The constitution of these alloys has been described by Dix and Heath³ and by Gwyer and Phillips⁴. The eutectic composition is indicated at 11.6% silicon, both with and without the presence of commercial amounts of iron. This composition is widely used in commercial practice on account of the facility with which it handles in the casting operation. Although chill casting and die casting probably displace the eutectic composition and temperature to the "modified" point (13-14% Si), results in practice are that with 13% silicon, castings may show some free silicon (with consequent decrease in ductility) at points where the chilling is, for some reason, insufficient, while with silicon from 11-12.3% free silicon is much less evident, and the casting and physical properties are entirely satisfactory.

The aluminum-silicon alloys offer, in general, resistance to corrosion which is superior to that of the alloys of which copper is a constituent. For maximum cor-

³E. H. Dix, Jr., and A. C. Heath, *Equilibrium Relations in Aluminum-Silicon and Aluminum-Iron-Silicon Alloys of High Purity*, Proc. Inst. Metals Div., A.I.M.E., 1928, v. 78, p. 164.

⁴A. G. C. Gwyer and H. W. L. Phillips, *Constitution and Structure of the Commercial Aluminum-Silicon Alloys*, J. Inst. Metals, 1926, v. 36, p. 283.

rosion resistance, zinc, tin, and particularly copper should be substantially absent or held to an absolute minimum.

Aluminum-Silicon-Copper, and Aluminum-Silicon-Copper-Nickel Alloys—While the series of aluminum-silicon alloys combine advantages in casting properties and corrosion resistance over the series of aluminum-copper, the latter are occasionally preferred for special purposes such as ease of machining and brighter color. Silicon imparts a slightly bluish tinge to the aluminum alloys. The commercial use of the aluminum-silicon-copper series, therefore, has been a natural and successful result of efforts to combine the advantages of both the preceding types. Nickel additions to aluminum die casting alloys are especially useful in brightening the color. A comparatively wide variety of analyses used in commercial practice for these alloys is largely a reflection of varying individual preferences among manufacturers and users. Some typical alloys are given in Table I.

The alloys of aluminum with one or more of the elements copper, silicon, and nickel cover all but a small percentage of present commercial alloys. Other elements such as manganese, iron, zinc, and tin, except where present in small amounts as impurities, are not usually found.

Magnesium has not hitherto been used extensively as an alloying element in aluminum die casting because the resulting alloys tend to be sluggish and are difficult to cast. Changes in die casting methods are tending to overcome this difficulty and may result in a more extensive use of this class of alloys. They offer the advantages of good physical properties and retain good color and luster after polishing.

Impurities in Aluminum Alloys—Aluminum alloy die castings are not critical to the presence of small amounts of impurities which may be present in commercial grades of primary aluminum or of the better grades of secondary aluminum, as has been shown by the extensive test program carried out by Committee B-6 of the A.S.T.M.

Secondary aluminum alloys are used extensively and quite satisfactorily in the production of commercial aluminum die castings. With the use of proper remelting conditions and adequate analytical control, scrap aluminum of suitable purity and cleanliness can be used, either with or without addition of primary aluminum, for the production of the alloys commonly called for in commercial specifications. Clean sheet clippings constitute an excellent source of secondary aluminum. Clean scrap castings of known composition may also be used to the extent that the composition corresponds or can be corrected by the addition of other metal, to that of the desired alloy. Because of the tendency of the alloys to pick up iron during the die casting process, the iron content of the alloy ingot should be held as low as commercially practicable.

Commercial die castings usually contain more than 1% of iron regardless of the original source of the metal. Iron is absorbed by the molten alloy from the melting pot and other parts of the die casting machine. The amount which may be present without harmful effect varies to some extent with the nature of the alloy. In some die casting alloys, the maximum percentage of iron is specified as 2.5%; in only one commercial alloy (No. IX, Table I) is the limit set at less than 2% (1.8%). Iron acts as a hardener in all of the alloys and when present in excessive amount, causes the alloy to be sluggish in the casting process and reduces the elongation and shock resistance of the resulting die casting.

Manganese has an effect somewhat similar to iron, but 0.75% or less in the aluminum-silicon alloys is of some slight advantage in counteracting the coarsening and embrittling effect of excessive iron. Small additions of chromium may also be made to these alloys to accomplish the same result.

Nickel is not regarded as a harmful element in those alloys containing copper.

Zinc is undesirable, producing "hot-shortness" in the casting operation, and its presence in amounts exceeding 1% indicates heavy use of low-grade aluminum scrap. Zinc is preferably kept below 0.75%.

For some applications in which the requirements are unusually exacting, it may be desirable to limit the impurities more closely than is necessary for the general run of commercial die castings.

Typical Commercial Alloys—The selection of aluminum die casting alloys for various purposes has resulted in wide variety of mixtures. Committee B-6 of the A.S.T.M. conducted a large number of physical tests on about 12 different mixtures. Eight of these alloys, as given in Table I, are quite representative of the range

Table I
Aluminum Die Casting Alloys

Alloy No.		Copper	Nominal Composition, % Silicon	Nickel	Aluminum
IV	Al-Si Series	{..	5	....	Balance
V		{..	12	....	"
VI	Al-Cu-Si Series ..	{2	3	....	"
VII		{4	5	....	"
VIII	Al-Cu-Si-Ni	{1.5	1.5	2 25	"
IX		{4	1.75	4	"
XI	Al-Cu-Si Series ..	{2	8	....	"
XII	Al-Cu Series	{7	1.5	....	"

of present commercial die casting alloys. Compositions may vary somewhat from those in the table according to particular requirements.

Alloy No. IV, V, VII, and XII, as given in Table I, are the most extensively used, but No. VI, VIII, and IX together with slight variations or combinations have certain applications.

Physical Properties—It should be thoroughly understood that mechanical properties quoted for die casting alloys are usually based on tests of special test bar specimens. Differences of several thousand psi. are found between flat test specimens $\frac{1}{2} \times \frac{1}{2}$ in. in the test section and round test specimens $\frac{1}{4}$ in. dia. in the test section. Individual specimens cut from die castings give widely different results, depending on casting thickness and manufacturing practice. The results of tension and impact tests on bars that were tested without machining, as given in Table II, are most useful as a comparison of the physical properties of different compositions in pressure-cast test pieces under identical conditions.

Table II
Physical Properties of Aluminum Die Castings¹

Alloy No.	Ultimate Strength Psi. ($\frac{1}{4}$ In. Round Specimen)	Elongation in 2 In., %	Charpy Impact, Ft.-lb. to Break Specimen ($\frac{1}{4} \times \frac{1}{4}$ " Sq. Specimen)	Sp.Gr. (Approx.)
IV	29,000	3.5	4.5	2.70
V	33,000	1.5	2.0	2.66
VI	30,000	3.5	5.0	2.75
VII	32,000	2.0	2.5	2.78
VIII	29,000	4.0	4.5	2.72
IX	31,000	1.5	2.0	2.87
XI	32,000	1.7	3.0	2.68
XII	33,000	1.0	1.5	2.85

¹Specimens pressure-cast and tested without machining.

Selection of alloy for a given die casting depends largely on the type, size, and use of the casting. In addition to casting and physical properties, consideration must often be given to such items as color, machinability, ease of plating, surface hardness, and resistance to corrosion.

Machining Aluminum Die Castings—Extensive machining operations on die castings are not usually called for and ordinarily consist of light turning, reaming or edge milling, and the tapping or milling of internal threads. External threads are usually cast with sufficient accuracy to require only light chasing. The general principles of tool design given by R. L. Templin elsewhere in A.S.M. Metals Handbook for machining aluminum are applicable to the machining of aluminum die castings.

For turning operations on aluminum-silicon alloys, tool bits or tips of the tungsten carbide materials have been found to last from ten to twenty times longer without regrinding than the best grades of high speed steel with the same feeds and slightly higher cutting speeds.

Finishing Aluminum Die Castings—For many uses the natural finish of aluminum alloys, as produced from the dies, is satisfactory. When desired, a wide choice of special finishes are available at varying costs. Commercial finishing operations are as follows:

Sand Blasting—Sand blasting can be performed in any standard equipment which is suitable to the size and quantity of the work. A fine clean sand should be used (such as No. 1½ flint) and renewed frequently to avoid discoloration. A sand blasted surface tends to show finger prints and other handling stains, which can be overcome by dipping the sand blasted die casting into a thin oil. Sand blasting forms an excellent preparation for painting, enameling, and lacquering.

Painting and Lacquering—These operations can be applied by ordinary standard methods of spraying, brushing, or paint dipping. Chemical treatment of the surface is not necessary for good paint adherence, and the only precaution to be observed is the cleaning of the surface (by sand blasting or washing with commercial cleaners). If this cleaning is not feasible, a priming coat of asphaltum-base paint may be applied directly to the surface of the casting. Anodic treatment (see below) forms an excellent base for painting on die castings to be subjected to exceptionally severe weathering or corrosive conditions, but is ordinarily not necessary.

The mechanical properties and dimensions of aluminum die castings are not adversely affected by temperatures (400-500°F.) used in ordinary Japanning operations.

Scratch Brushing—The finish commonly known as "scratch brush" or satin finish is similar in appearance to roughly etched glass. As the name implies, this finish is accomplished by a revolving wire scratch brush. Caution should be exercised to have castings thoroughly cleaned of oil or dirt. The most satisfactory scratch brush finish is obtained on castings which have been first subjected to an acid dip (See "Bright Dipping").

Bright Dipping—Bright dipping is commonly practiced to impart a dull white, somewhat satiny appearance to various fabricated forms of aluminum, including die castings. Alloys used in the latter usually contain a certain percentage of added silicon. Therefore, it is necessary after etching the castings with caustic or alkaline cleaning solution that the acid bath used for brightening the castings should consist of a mixture of hydrofluoric and nitric acids, which dissolves the silicon set free by the etch. A muriatic-nitric acid mixture is commonly used for aluminum sheets and aluminum-copper alloy castings. The hydrofluoric-nitric mixture necessitates the use of a dipping tank lined with chemically pure lead.

Failures to produce satisfactory results in bright dipping aluminum-silicon alloy die castings are sometimes attributable to attempts to use muriatic instead of hydrofluoric acid or to use the latter in a stone crock or the like, or by using acid which has become neutralized or diluted, or by using acid which has a top coating of oil accumulated by dipping improperly cleaned castings.

In handling the hydrofluoric-nitric acid mixture great care must be exercised not only for the protection of clothing but to avoid severe acid burns.

Ball Burnishing—Ball burnishing affords a highly economical means of putting a satisfactory grade of polishing on small die castings, although it is not equal to the regular emery, polish, and color-buff operations. The castings are agitated in a wood-lined barrel with a soap solution and steel balls.

Anodic Treatment and Coloring—Aluminum die castings can be anodically treated to produce an artificial film of oxide on the surface for protection against corrosion or a surface that can be dyed or painted.

Polishing—The following polishing operations impart the highest degree of mirror-like finish to die castings such as vacuum cleaner parts, domestic utensils, and ornamental work:

1. Emery—(glued rag wheel)
2. Emery—(felt wheel)
3. Buff—(stitched rag wheel)
4. Color—(built-up rag wheel)

The first emery operation may be conducted with No. 100 emery or coarser, depending on the amount of preliminary dressing of the surface necessary to remove nicks, scratches, and die checks. However, before proceeding to buff and color, the entire surface should be ground with emery of No. 150 grade or finer. On castings with plain uninterrupted surfaces, the felt wheel emery operation can frequently be omitted. Otherwise it is useful in avoiding "drag marks" due to rag

wheels catching in the edge of cored holes. A somewhat lower grade of finish can be accomplished at considerable saving in cost by eliminating the emery operations and simply buffing and coloring.

Plating of Aluminum Die Castings—Aluminum die castings can be plated with any of the common plating metals such as nickel, brass, chromium, and silver. The following procedure should be sufficient to enable any experienced plater to obtain satisfactory results:

1. Grind and buff to required finish.
2. Remove grease with an organic solvent or by dipping for a short time in a hot, mildly alkaline cleaner. A good cleaner consists of 1-3 oz. per gal. each of sodium carbonate and trisodium phosphate.
3. Rinse in clear cold water.
4. Dip in the following solution:

Nitric acid (sp.gr. 1.42).....	3 parts
Hydrofluoric acid (48-52%).....	1 part
Temperature	75-80°F.

The proper timing on this dip must be carefully determined by experiment, as it is the important step in the plating procedure. This is accomplished by plating samples at different times of dip, observing them, breaking them, and noting the adhesion. A properly dipped sample will show no flaking of the nickel from the aluminum and should polish readily to a high finish. Under-dipped samples show poor adhesion, while over-dipped ones do not polish readily to a high luster. Each alloy composition will have a dipping time most suited to it. Although the differences between alloys are slight, the dipping range for each alloy is wide. Usually the proper time of dip lies between 15 and 30 sec. Due to the wide dipping range the effect of temperature on the action of the dip is not very great, but as a rise in temperature speeds up the action of the dip, a correction in the dipping time is sometimes necessary.

5. Rinse in clear cold water.
6. Plate at 15 amps. per sq.ft. in the following nickel bath:

Single nickel salts (nickel sulphate).....	19 oz. per gal.
Magnesium sulphate	10 oz. per gal.
Ammonium chloride	2 oz. per gal.
Boric acid	2 oz. per gal.

The time of plating should be determined to give the desired corrosion resistance. A time of plating of 1 hr. is suggested, but this can be reduced later if it is found that thinner plate meets the service requirements. It is advised that racks with spring brass holders be used, such as are customary for chromium, to facilitate handling and insure a good contact. Other nickel solutions such as used on zinc may be substituted for the above.

7. Rinse in cold water and dry by means of a hot water dip.
8. Polish nickel.
9. Clean and plate with any desired metal, such as brass, chromium, bronze, or silver, using standard commercial methods for plating these metals.

Chromium Plating—Chromium can also be plated directly on aluminum die castings using the following steps:

1. Grind and buff to desired finish.
2. Remove grease by dipping a short time in a hot, mildly alkaline cleaner. Same cleaning solution as given for nickel plating.
3. Rinse in clear cold water.
4. If the aluminum surface is not white, dip in the following solution for a short time:

Nitric acid (sp.gr. 1.42).....	3 parts
Hydrofluoric acid (48-52%).....	1 part

If the surface is still not white, as is occasionally the case, the work should be briefly dipped in equal parts of concentrated nitric and sulphuric acids.

5. Rinse in clear cold water.
 6. Plate in an ordinary chromium bath. If a polished finish is desired, use the bath cold and polish the work with a good grade of chromium polishing compound. Hot chromium baths give whiter deposits which are difficult to buff.
- A 3 to 15 minute chromium plate from a cold bath may be used for work to be buffed. Hot chromium solutions are best suited for heavy deposits.

Oxidized and Colored Finishes—Oxidized and colored finishes on copper, brass, and silver plated aluminum die castings can be produced by using the same methods commonly employed in obtaining these finishes on the solid metals, or plated base metals other than aluminum. Oxidized finishes should be protected by a thin coat of lacquer.

Cold and Hot Forming Aluminum Alloys

By C. F. Nagel, Jr.,* and P. V. Faragher*

General—Aluminum and its alloys, like other metals, strain harden when worked below their annealing temperatures. The increase in the tensile strength based on the strength of the alloy in the annealed (or heat treated) temper is directly proportional to the amount of cold work expressed as the fractional reduction of the initial cross sectional area. This direct proportionality applies throughout most of the range normally used in commercial manufacturing operations. For higher reductions the tensile strength increases more rapidly than would be indicated by this relationship.

The yield strength of annealed (or heat treated) material, that is, the stress which produces a permanent set of 0.2%, is increased materially by the first small amounts of cold work, succeeding reductions producing relatively less effect, until after about 20% reduction in cross sectional area the rate of increase in this property parallels quite closely the increase in tensile strength.

The elongation decreases with increasing amounts of cold work, and, as in the case of the yield strength, the first small amount of cold work produces a relatively greater effect (in this case, a decrease) than subsequent reductions of equal amount. The first reduction of 20% usually reduces this property to about $\frac{1}{2}$ of its initial value or even less; while after a reduction of about 60%, further cold working causes little additional change in this property.

From the foregoing discussion it will be seen that the higher the tensile strength in the annealed (or heat treated) temper, the greater the amount of hardening when the metal is subjected to cold forming operations. The workability of a material cannot be judged, however, from its tensile strength alone, nor is the per cent elongation an adequate criterion. The spread between the yield strength and the ultimate tensile strength, or perhaps the ratio of these properties, has considerable bearing on the amount of cold forming which can be done without failure. Other qualities which are not determined in the tension test or by other standard methods of test, used in the inspection of metal products, also have an effect, since alloys having substantially the same physical properties may have markedly different forming characteristics.

Cold Working—The relative ease of forming the various grades and tempers, as well as the amount of forming which can be done, varies with the nature of the operation, and the type and condition of the equipment. Consequently, the trial of samples on the tools which are to be used in production finally determines the suitability of an alloy for a given application.

Ease of forming is one of the qualities of aluminum which has contributed to its widespread use. This quality is retained in varying degrees in different commercial alloys.

For drawing or stamping operations, the tools may be of cast iron, semisteel, or tool steel. For difficult jobs the condition of the surface of the die, punch, and blank holder may determine the difference between successful operation and failure. For difficult work the tools should be of tool steel and should be well polished. A slight increase in the radius around which the metal is formed may overcome difficulties experienced in forming the harder alloys on tools originally designed for more workable metals.

For most drawing operations the light lubricating oils, known as "metal oils", give excellent results. For difficult work, tallow mixed with a small amount of mineral oil is recommended.

Bending equipment and forming rolls used for other metals are used successfully to form aluminum alloys. The radius for bends, in terms of the section thickness, is usually greater for heavy sections than for thinner. The actual radius required for a given material can be determined by trial. The following table will serve as a preliminary guide in the choice of an alloy for a required bend or of the radius to be used with the aluminum alloys in common use:

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Approximate Radii for 90° Cold Bend of Aluminum and Aluminum Alloy Sheet

Minimum permissible radius varies with nature of forming operation, type of forming equipment, and design and condition of tools. Minimum working radius for given material or hardest alloy and temper for a given radius can be ascertained only by actual trial under contemplated conditions of fabrication.

Alloy and Temper†	Bend Classification*	Alloy and Temper†	Bend Classification*
2S-O	A	A17S-O	B
2S-¼H	B	A17S-T	F
2S-½H	B		
2S-¾H	D	24S-O¹	B
2S-H	F	24S-T¹, §	J
		24S-RT¹	K
3S-O	A		
3S-¼H	B	51S-O	A
3S-½H	C	51S-W	F
3S-¾H	E	51S-T	K
3S-H	G		
4S-O	B	52S-O	A
4S-¼H	D	52S-¼H	C
4S-½H	E	52S-½H	D
4S-¾H	G	52S-¾H	F
4S-H	H	52S-H	G
17S-O¹	B	53S-O	A
17S-T¹, §	H	53S-W	F
17S-RT¹	J	53S-T	G

Composition of Alloys

- 2S—Commercially pure Al—Min. of 99% Al.
 3S—Mn 1.25%. Balance Al and impurities.
 4S—Mn 1.25%, Mg 1%. Balance Al and impurities.
 17S—Cu 4%, Mn 0.5%, Mg 0.5%. Balance Al and impurities.
 A17S—Cu 2.5%, Mg 0.3%. Balance Al and impurities.
 24S—Cu 4.2%, Mn 0.5%, Mg 1.5%. Balance Al and impurities.
 51S—Si 1.0%, Mg 0.6%. Balance Al and impurities.
 52S—Mg 2.5%, Cr 0.25%. Balance Al and impurities.
 53S—Si 0.7%, Mg 1.25%, Cr 0.25%. Balance Al and impurities.

*For corresponding bend radii see following table:

†Designation of Symbols: O = annealed; H = fully cold worked (hard); ¼H; ½H; ¾H = intermediate degrees of cold working between "O" and "H"; T = heat treated and aged; RT = heat treated, aged, and cold worked; W = precipitation heat treatment.

Radii Required for 90° Bend in Terms of Thickness, t

		Approximate Thickness					
Bend Classification	B&S Gage In.	26 0.016 ⅛	20 0.032 ⅜	14 0.064 ⅜	8 0.128 ½	5 0.189 ⅜	2 0.258 ¼
	A	0	0	0	0	0	0
B	0	0	0	0	0	0-1t	0-1t
C	0	0	0	0	0-1t	0-1t	½t-1½t
D	0	0	0	0-1t	½t-1½t	1t-2t	1½t-3t
E	0-1t	0-1t	½t-1½t	1t-2t	1½t-3t	2t-4t	2t-4t
F	0-1t	½t-1½t	1t-2t	1½t-3t	2t-4t	2t-4t	2t-4t
G	½t-1½t	1t-2t	1½t-3t	2t-4t	2t-4t	2t-4t	2t-4t
H	1t-2t	1½t-3t	2t-4t	2t-4t	2t-4t	2t-4t	2t-4t
J	1½t-3t	2t-4t	2t-4t	2t-4t	2t-4t	2t-4t	2t-4t
K	2t-4t	3t-5t	3t-5t	3t-5t	3t-5t	3t-5t	3t-5t

¹Alclad 17S and Alclad 24S can be bent over slightly smaller radii than the corresponding tempers of the uncoated alloy.

§Immediately after quenching, these alloys can be formed over appreciably smaller radii.

Hot Forming—The wrought aluminum alloys are of two types: 1. Those whose various tempers are produced by definite amounts of strain hardening by cold work; and 2. those which are susceptible to heat treatment processes. The use of hot forming is more limited in the case of the first class than in that of the second.

Aluminum alloys are plastic at elevated temperatures up to a temperature range just below the melting point, within which they become brittle or "hot short".

Hot forming has a limited application among the alloys which depend upon strain hardening for their harder tempers. In the soft tempers all of them have good forming qualities; if they are heated in the harder tempers, care must be taken to avoid heating to the annealing temperature, otherwise they will be softened and will remain soft on cooling to room temperatures. Considerable improvement in the bending qualities will be gained by working at a temperature of 300-400°F., in which range there is little loss in strength and hardness on cooling to ordinary temperatures. At temperatures above 600°F. they are quite plastic, but on cooling to ordinary room temperatures they are practically in the annealed state.

In the case of the heat treatable alloys, heating may affect not only the mechanical properties but in some of the alloys may also impair their normal resistance to corrosion. Heating to 400°F. materially improves the forming qualities of the heat treatable alloys, and if held at this temperature for not more than a half hour, the loss in tensile properties does not exceed a few per cent of their normal values. In the case of 53S, 51S, and 27S, there is little change in the resistance to corrosion of the material, but in 17S and 24S this property is impaired appreciably, and particularly in the nature of the attack.

At temperatures in the heat treatment range the heat treatable alloys are quite plastic and can be severely and easily deformed. They may be reheat treated after forming or the heat may be removed by the forming dies with sufficient rapidity to constitute a quench (U. S. Patent 1,751,500), so that the properties of the heat treated tempers are developed after suitable aging. For some operations, somewhat lower forming temperatures give better results, in which case the part may be reheated to the heat treatment temperature and quenched in the die. This avoids the possibility of distortion which frequently results when the part is quenched in water. For success with this method, the dies must contain sufficient metal to provide a rapid cooling of the alloy.

Heat Treatment of Wrought Aluminum Alloys

By C. F. Nagel, Jr.,* and P. V. Faragher*

Since the articles for the individual aluminum alloys give the temperature ranges for heat treatment and the physical properties thus obtained, this article will discuss the heat treatment processes† which are actually used and the general principles involved.

General—There are several alloys of aluminum which can be wrought into desirable commercial forms and which can have their physical properties improved by heat treatment. In every case the hardening constituents in these alloys are substances whose solid solubility in aluminum is distinctly higher at elevated temperatures than at room temperatures. There are no phase changes in solid aluminum below the melting point, consequently grain refinement is not a factor in the improvement in properties. In aluminum alloys heat treatment is simply a means of more efficiently distributing the alloying ingredients so that they more effectively perform their function of hardening the metal.

Because of the complicated equilibrium relations which exist between the liquid and the solid which freezes from it, and the fact that equilibrium conditions are not maintained during the rapid freezing of commercial rolling ingots, the percentage of alloying elements varies from the center to the outside of the individual grains. An appreciable percentage of the added hardening elements is present in the form of relatively large particles of a rich alloy, or of eutectic, distributed throughout the cast ingot. These conditions persist in spite of the fact that the total amount of the hardening elements is completely soluble in solid aluminum at temperatures just below the melting point when equilibrium conditions are established.

The working of the alloy tends to break up the cast structure of the ingot and thereby increase the rate of solution of the alloying constituents when the metal is subsequently heated. In general, the heat treating temperature is made as high as possible without melting any of the eutectic material which is present in a particular alloy. At the high temperature, solution and diffusion take place to produce practically a homogeneous solid solution. The alloy is then quenched so that there is not time for the hardening elements to precipitate from solid solution during the cooling period, in accordance with their lower solubility at lower temperatures. This process is called "solution heat treatment."

On standing at ordinary temperatures the alloying constituents tend to precipitate from solid solution and to agglomerate into larger particles in accordance with their true solubility relations at room temperatures. In some of the alloys the rate of this change is so slow at room temperatures, that they must be heated slightly (around 300°F.) to increase the rate of these processes. It should be noted that the larger particles formed during "aging" or "age hardening" at room temperatures, or "artificial aging" (commonly called "precipitation heat treatment") at slightly elevated temperatures, are usually too small to be resolved by the microscope. By prolonged heating it is possible, in all cases, to cause growth to a size visible under the microscope. The size of particle which results from aging or from proper precipitation heat treatment is more effective in hardening the metal than the molecules of alloying constituents which are present in solid solution and also more effective than the larger particles which result from prolonged heating or "overaging."

The foregoing outlines the theory presented by Merica and his associates to explain the observed facts in the heat treatment of aluminum alloys. It may not completely describe the phenomena which occur, but with the slip interference theory of Jeffries and Archer, which pictures the particles as keying the crystal planes against slip, it gives a mechanical analogy which is easy to remember and explains the nomenclature in common use for these processes.

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†Attention is called to the fact that certain heat treatment processes and the heat treatment of certain alloys are subject to patent restrictions. The responsibility for securing the necessary authority to use the practices described rests solely with their user.

Thermal Treatment Processes—Three types of thermal treating processes are applied commonly to wrought aluminum alloys:

1. Solution heat treatment consists in heating the alloy to a temperature at which certain constituents go into solution, usually upwards of 900°F., followed by quenching to maintain constituents in solution and thus increase the mechanical properties above those of the soft or annealed temper.

2. Precipitation heat treatment, required by certain alloys, consists in heating them ordinarily after the solution heat treatment, at a moderate temperature, usually around 300°F., to reprecipitate constituents and to further increase their strength and hardness, although usually at some sacrifice in elongation. In some cases the process of fabrication leaves the alloy in a state of partial supersaturated solid solution, and the application of a precipitation heat treatment alone results in hardness and strength increases of practical importance.

3. Annealing consists in heating the alloys to remove strain hardening resulting from cold working the metal or to remove the effects of heat treatment, or both.

Thermal Treating Practice—Solution Heat Treatment Furnaces—Aluminum alloys are commonly heat treated in molten salt baths or in air furnaces. The salt bath consists either of fused sodium nitrate, or, if the bath is also to be used for annealing, a mixture of equal parts of sodium and potassium nitrates. Provision should be made for the proper circulation of the bath throughout the immersed load of metal to insure uniform temperatures in all parts of the bath. The bath in a steel or cast iron tank is heated with gas, oil burners, or electricity.

Air furnaces are usually heated electrically with the elements having low energy input per unit of radiating surface or so shielded that they do not radiate directly onto the charge. The furnace design must be such that the temperature in all parts of the working zone is within the range specified for the heat treatment of the alloy. Better results are obtained if the furnace is provided with means for air circulation. Other methods of heating which give uniform temperatures throughout the furnace are satisfactory, but less convenient in operation.

For heat treating small parts such as rivets, a small gas or oil heated pot of molten nitrate or lead is frequently used. The parts are placed in a steel tube with the bottom closed and the top covered, the tube immersed in the bath to within a short distance of the top.

Precipitation Heat Treatment Furnaces—Precipitation heat treatment is usually carried out in a furnace or oven heated electrically or by pipes containing steam under pressure. Provision for circulating the air is usually made to provide a uniform temperature throughout the furnace as well as more rapid heat transfer.

If electrical heating is used, the units should be of the type having a low energy input per unit of area. The baffles used to direct the air circulation may also serve to minimize direct radiation to the charge.

If steam is used, the temperature is readily controlled by proper regulation of the steam pressure. Except in the case of heavy stock in which minor surface action is of no consequence, furnaces in which the steam comes in contact with the charge are not used.

For small articles an oil bath serves adequately. Gas or oil fired furnaces may be used only if designed so as to permit the required temperature control.

Annealing Furnaces—Annealing furnaces are usually oil or gas fired, since the permissible temperature range for this operation is more than for the solution or precipitation heat treatment processes. Electric furnaces are also used.

Pyrometric Equipment—Since accurate temperature control is essential for best results, all pyrometers are calibrated at regular frequent intervals. Automatic temperature recorders are desirable, if not essential, to provide a record of the heating period as a means of insuring that the material has been heated for the required time at the desired temperature range and that it has not been overheated. Furnace operation is simplified by automatic temperature regulating equipment, but manual control is possible.

Solution Heat Treatment—Wrought aluminum alloys in large tonnage are heat treated successfully without difficulty. Therefore, the following detailed instructions and precautions should not be interpreted to mean that proper heat treatment of wrought alloys is a difficult process which cannot be carried out under commercial conditions. Proper practices are necessary to get satisfactory results, but with ordinary care the required methods are established readily on a normal operating basis.

The temperature of the salt bath or of the furnace should not be higher than the maximum heat treatment temperature specified for the alloy, either when the

load is inserted, or at any time during the heat treatment period. This maximum temperature is chosen as high as possible without exceeding the melting point of the eutectic which is present in the alloy. If this eutectic is melted during heat treatment, the mechanical properties and usually the surface appearance of the alloy are seriously injured.

If the alloy is not heated to the minimum temperature specified, the full mechanical properties are not developed and, in some cases, the resistance to corrosion of the resulting product is below standard.

It is not possible to obtain satisfactory results by heat treating successively different parts of a piece of metal. It must be uniformly heated throughout and quenched in all parts in the same operation.

The heating time varies with the nature of the product, the alloy, the type of furnace, the size of load and other factors. It is essential that all parts of the load be heated for a sufficient time to insure the development of the properties required for the alloy. This time of heating, after all of the load has reached the heat treatment temperature range, may be as little as 5 min. for thin gage 17S sheet (Cn 4%, Mn 0.5%, Mg 0.5%, balance Al) heated in a nitrate bath, to as much as 2 hr. for thick 24S plate (Cn 4.2%, Mn 0.5%, Mg 1.5%, balance Al), or 5-12 hr. for forgings of heavy section heated in air furnaces. This distinction between salt baths and air furnaces is made because of the slower rate of heat transfer in the latter and the element of uncertainty that all parts of the load are actually at the required temperature. The actual times required will be ascertained from experience in operating the available equipment with the types of material which are being used. The consistent development of the desired mechanical properties in the product is the criterion.

In the case of Alclad products, the minimum possible time should be used in order to avoid diffusion of the alloying constituents of the core through to the surface. Since different thicknesses of metal require different times of heating, it is preferable that Alclad products of greatly different thickness shall not be heat treated in the same load.

Quenching—After heating the alloy for the required time, it is removed and quenched. The time interval from the removal of the load from the heating bath or furnace until it is completely immersed in the quenching medium should be as short as possible, and in any event should not exceed a few seconds. Particularly in the case of thin material, the use of guard sheets will minimize the loss of heat during the period of transfer. Allowing the metal to cool in the air is equivalent to quenching from a lower heat treatment temperature, and both mechanical properties and resistance to corrosion may be impaired. Quenching in hot water or oil, or in air, may develop the required physical properties, but the resistance to corrosion is usually less than that of material quenched in cold water. Such practice may be necessary, however, in some instances to avoid warpage. Relatively slow cooling from the solution treatment may be permissible with 53S (Si 0.7%, Mg 1.25%, Cr 0.25%, balance Al) and 14S (Cn 4.4%, Si 0.8%, Mn 0.75%, Mg 0.35%, balance Al) forgings, since the resistance to corrosion of these materials does not seem to be so dependent on cooling rate as that of some of the other heat treated alloys.

If the metal has been heated in a nitrate bath, it must be thoroughly washed to remove the salt completely since otherwise it may initiate corrosion of the material. For this purpose, warm water (150°F.) may be used after the metal has been quenched in cold water, because of the greater solubility and higher rate of solution of the salt at higher temperatures.

Precipitation Heat Treatment—Some of the aluminum alloys age harden at ordinary room temperatures, others must be heated to higher temperatures to develop their maximum properties. The temperature range and time vary with the different alloys and are shown on the data sheets for the alloys.

Annealing—The annealing practice varies depending upon the condition or temper of the alloy. The strain hardening resulting from working alloys which were originally in the soft temper may be removed and the alloy completely softened by heating to a temperature in the range of 640-670°F. Heating above 670°F. causes partial solution heat treatment and consequently prevents complete softening; at temperatures below 640°F. annealing is not complete.

This same practice, applied to the alloy which has been subjected to the solution heat treatment, will remove most of the effects of heat treatment as well as

any subsequent strain hardening, so that it is suitable for all but the more severe forming operations. If, however, the heat treated alloy must be completely annealed, it must be heated for 2 hr. at 750-800°F., then slowly cooled (not faster than 50°F. per hr.) until a temperature of 500°F. has been reached. The rate of further cooling to room temperature is not important.

Nomenclature—The various wrought aluminum alloys commercially available in this country at the present time are designated by the principal manufacturer with a number followed by the letter "S" to indicate that the symbol applies to wrought material. The number may be preceded by a letter to indicate a somewhat modified composition from that of the parent alloy, for example, A17S.

The various tempers are designated by letters following the alloy symbol and separated from it by a dash, for example, A17S-T. Where more than one heat treatment is applied, the different heat treatments may be indicated by a numeral following the letter, for example, 11S-T3.

The temper resulting from complete heat treatment (including whatever aging is necessary to develop the maximum properties from heat treatment) is designated by the letter "T". The letter "W" is used only with the alloys which require precipitation heat treatment to develop their maximum properties to indicate that they have been subjected only to the solution heat treatment, for example, 53S-W. In some of these alloys there is some aging at room temperatures even though precipitation heat treatment is necessary to develop their higher properties. In these cases, the properties specified for the "W" temper are those which the material will have after a few days when this aging is practically complete. The soft temper which results from annealing is designated by the letter "O".

The alloys 17S and 24S age spontaneously at room temperatures, consequently there is no "W" temper. Immediately after quenching they are more plastic and more easily formed than after they have had time to age. (See the article in this handbook "Cold and Hot Forming of Aluminum Alloys.") Aging of these alloys, as measured by the change in physical properties, is at first quite rapid and proceeds at a gradually diminishing rate until in about four days it is practically complete.

Nitrate Hazard—Although fused nitrate baths are commonly used in the heat treatment of steel as well as aluminum, it is felt that attention may well be called here to certain dangers in their operation. Care should be taken to prevent contact of the fused salt with carbonaceous or organic material (wood, charcoal, coke, oil, or cloth) or with red hot iron or steel. Articles to be heat treated, or sludge, should not be allowed to lie on the bottom of the tank, especially if the tank is underfired, as they are apt to cause the tank to become locally overheated and be burned through. The possibility of combustible gases accumulating around the tank should be guarded against, and it is desirable to have at some distance from the tank a gas or oil shut-off valve which can be operated in emergency. Care should be taken not to put anything wet into the nitrate bath. Extra sacks of nitrate should be stored in a dry place and at a distance from the tank. Care should be exercised in adding fresh salts to the bath if at all wet; this is best done when the bath is frozen. In melting a solid bath, the salt must melt freely at the sides of the tank before melting at the bottom, to avoid generation of pressure and possible explosion. In case of a nitrate fire, avoid the use of water or of any fire extinguisher containing water. Perhaps the best fire extinguisher is dry sand, a supply of which should be kept near the tank.

Machining Aluminum and Aluminum Alloys

By R. L. Templin*

General—Aluminum and most of its commercial alloys have good machining characteristics but these characteristics differ somewhat from those of the other commonly used metals. While the tools ordinarily used for cutting steel will often give satisfactory results on aluminum and its alloys, best results will be obtained if the methods herein described are followed.

A free machining aluminum alloy is available with machining characteristics that make it better suited than the other aluminum alloys for many of the operations performed on high production machine tools.

The following instructions are divided into two parts. Part I describes recommended tools and procedure for general machine shop practice. Part II deals specifically with automatic screw machine practice.

Part I

General Machine Practice

Tool Materials—Plain high carbon tool steels perform satisfactorily in the machining of aluminum and most of its alloys, and this tool material is widely used. For quantity production work, however, high speed tool steels have replaced plain high carbon tool steels to a large extent. Tools tipped with cemented tungsten carbide show a marked improvement over both high carbon and high speed tools. Their cutting edges remain sharp much longer without regrinding and they produce a better surface finish. In fact, tungsten carbide tools are necessary for best results with aluminum alloys of a high silicon content.

Tool Shapes in General—Tools for cutting aluminum and its alloys, with the exception of the free cutting alloys, should have appreciably more top rake and side rake than those for cutting steel. Clearance is also important. In many cases the shapes are not appreciably different from those of the tools commonly used for cutting hardwoods.

Top Rake—Often the top rake is called "hook" because of the hook-like appearance it gives to the tool. It should vary from 30-50°, depending on the type of tool used, as required by the nature of the work.

Clearance—The clearance should be about 8-10°. This angle, plus the top rake angle indicated, leave about 32-52° for the total included angle of the cutting edge of the tool.

Clearance is important and must be carried around the side of the tool which advances into the work. If too small, the side of the tool will rub against the work and generate heat. If too large, the tool may tend to dig into the work and chatter.

Side Rake—A side rake of from 10-20° materially assists in the cutting action of the tool, since it tends to produce a slicing action and thus causes the tool to cut the metal more freely. Planer finishing tools have been ground with a side rake as high as 60°, in order to take full advantage of the free cutting characteristics of aluminum.

The cutting tool angles previously described apply to machining aluminum in general. While there are some tools to which these angles may not be adapted, they can be applied to many types to produce the best results. Specific values for the different angles are governed by the work to be done and the requirements of the machine in which the tool is used.

Tool Finish—In all cases it is essential that the cutting edges be keen, smooth, and free from grinding wheel scratches, burrs, or wire edges. Too much emphasis cannot be given to this requirement, because on it depends to a large extent the success of machining aluminum and its alloys. Keen edges are best obtained by finish grinding on a fine abrasive wheel, then hand stoning with a fine oilstone, or lapping, taking care that neither the angles nor the contour of the cutting edge are appreciably modified during the finishing operations.

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Lathe Tools—Outside turning tools for use in a lathe when machining aluminum and its alloys may be of the form shown in Fig. 1, but tools of this kind, when prepared from the usual tool bit stock, require considerable grinding in order to produce the desired shape, and it is sometimes difficult to maintain the values for the different angles when regrinding. A better tool is shown in Fig. 2. The bit of this tool is made from annealed high carbon or high speed steel. Resharpener is readily accomplished by holding the bit by its shank in the chuck or collet of a tool grinding machine or lathe, and grinding off the outside diameter until a keen edge is obtained. After each grinding, the tool should be stoned as previously indicated. When using such a tool and resharpening procedure, it is comparatively easy to maintain the desired shape throughout the useful life of the tool. Also, this tool has proved more economical than those ground from square or rectangular tool bit stock, and possesses certain adjustable features. When the clamp screw of the tool bit holder is loosened, the bit may be rotated to various positions and thus be adjusted to different working conditions. Tools of this form may be used for both rough turning and finishing cuts, but where the same tool is used for both it should be restoned before using as a finishing tool. With some modifications, either of these two forms of tools may be adapted for boring operations.

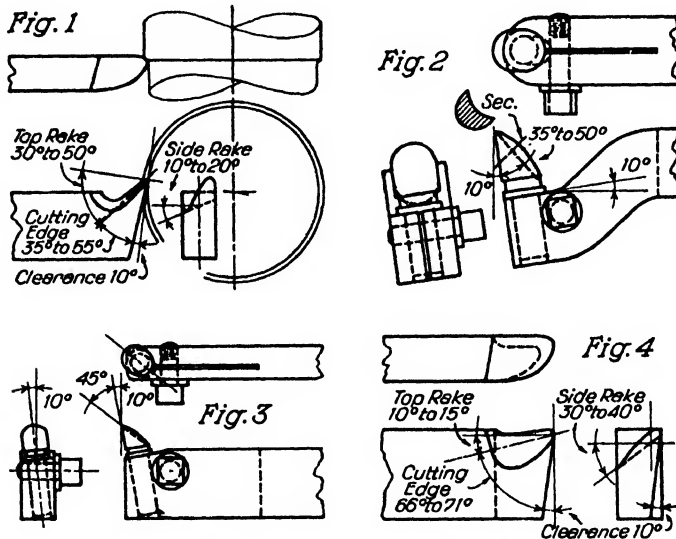


Fig. 1—Lathe tool that may be used with aluminum.

Fig. 2—Lathe tool recommended for use with aluminum.

Fig. 3—Planer and shaper tool for machining aluminum.

Fig. 4—Planer tool for roughing aluminum.

These tools, like most others suitable for machining aluminum and its alloys, tend to produce continuous chips, which usually are curled only a little when the tools are functioning properly. Decreasing the top and side rake angles tends to curl the chips more and hence to break them up. The extent to which this may be done and yet obtain the desired surface finish depends largely on the particular alloy that is being machined.

Parting tools for machining aluminum should have from 12-20° top rake and should be stoned so that their cutting edges are keen and smooth. With such tools the front clearance angle should be decreased to about 5-6°.

Facing tools should be ground so as to have a side rake similar in amount to that indicated for the top rake of the outside tools.

Planer and Shaper Tools—The tool shown in Fig. 2 can be readily adapted to planer and shaper work by using a holder, as shown in Fig. 3. Here again the tool may be used for both roughing and finishing work when machining aluminum, but a side cutting tool, as shown in Fig. 4, can be used to better advantage for heavier roughing cuts.

When finishing aluminum in a planer or shaper, care must be used to prevent the tool striking or rubbing on the finished surface during the return stroke of the tool. If the tool strikes, the work may be scratched and the thin edge of the tool broken.

Milling Cutters—Milling cutters, straddle mills, end mills, and similar cutters work to best advantage in machining aluminum and its alloys if they are of the coarse tooth spiral type and have a considerable amount of top rake on their cutting edges. In some instances milling cutters with nicked teeth assist in decreasing the chip size. Face milling cutters should be designed so that the inserted teeth have appreciable top and side rake. The helical milling cutters, primarily designed for machining steel, work especially well with aluminum and its alloys if the cutting edges are provided with suitable top rake. The same may be said of staggered tooth milling cutters.

Threading Tools—Excellent threads may be chased even in the softest aluminum with an engine lathe using a single pointed threading tool having considerable top and side rake. Hand and machine taps will produce smooth and accurate threads

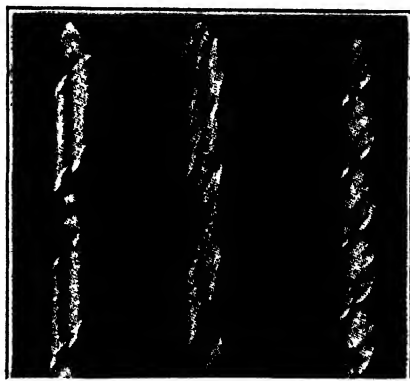


Fig. 5—Types of twist drills, $\frac{1}{8}$ -in. dia. From left: Single flute, 40° spiral angle; double flute or standard, 24° spiral angle; and special double flute, 47° spiral angle.

in aluminum if they are of the spiral flute, ground thread type. Experience has shown that such taps preferably should have a right-hand spiral flute when intended to cut a right-hand thread and the spiral angle should be similar to that used in an ordinary twist drill. Taps which have a short spiral ground on the front end, such as the "gun" tap or spiral pointed tap, will often work satisfactorily in aluminum when there is room for the chips to be forced ahead of the tap and when the thread to be cut is not tapered, but taps of this type are not satisfactory for taper threads or for use as bottom taps. When using spiral fluted taps, especially in automatic screw machines, it has been found advantageous to grind a top rake on the back of the lands so that there will be less tendency for the tap to tear the threads when backing out of the work.

Thread chasers for self opening die heads and collapsible taps should be ground with appreciable top and side rake. Certain makes of these tools lend themselves more readily than others to modifications of their cutting angles.

Twist Drills—Like all other cutting tools for aluminum, twist drills should have keen edges, and a copious amount of cutting compound should be used. The best drill for aluminum is one in which the flutes have a large spiral angle, that is, more twists per inch than the ordinary twist drill. Ordinary drills are suitable when the holes are not deep, and for some work the single fluted twist drills used on hardwood will work satisfactorily. Polished flutes both improve the cutting action of the drill and assist materially in chip removal.

When the hole is deep in proportion to its diameter, it may be necessary to withdraw the drill from the hole occasionally to dispose of the cuttings. A high speed and light feed are also helpful, especially for small size drills. Examples of twist drills suitable for use on aluminum and its alloys are shown in Fig. 5.

Reamers—Reamers of the spiral fluted type, such as are generally used for machining steel, produce the best results on aluminum.

Saws—Since sawing is fundamentally a cutting operation, the principles which govern the shape of machine cutting tools for aluminum should be followed, as far as practical, in the selection of saws for sawing aluminum. The front of the saw teeth should have considerable top rake or hook and generally some side rake, the latter depending upon the type of saw tooth used; a hook angle of from 10-25° is recommended. To use a saw with so much hook, the sawing machine must be provided with a positive feeding device to prevent the saw from feeding into the work too rapidly, and the work must be held firmly. For some of the rougher classes of work where it is desired to feed the work by hand, the saw teeth should have little, if any, hook, but never a negative rake.

It is important that proper clearances be provided on the sides of the teeth, otherwise the teeth will drag in the saw cut and cause the saw to overheat. Saws for cutting aluminum should have comparatively coarse teeth with curved gullets free from sharp corners and burred edges to eliminate danger of chips sticking.

Circular saws for aluminum may be operated at peripheral speeds of 10,000-15,000 f.p.m. Speeds in the neighborhood of 5,000 f.p.m. or more are recommended for band saws. To obtain high saw speeds, it is, of course, important to have a machine free from vibration, because this will cause fatigue failure of saw blades or saw teeth.

A relatively fine feed, in comparison to the peripheral speed, generally should be used to avoid large cuttings. The feed will depend largely upon the kind of work.

A cutting lubricant or coolant is necessary for some classes of work, especially when sawing large, heavy sections. Mineral base lubricating oils, thinned with kerosene, provide satisfactory lubrication when fed to the sides of the saw blade. Soluble oil cutting compounds have also been found satisfactory. In some instances, an occasional application of paraffin wax or heavy grease will provide ample lubrication.

Hand hack saw blades of the "wavy-set" type work especially well with aluminum.

Files—Files with single cut coarse teeth, having considerable top rake, or "hook", work best on aluminum and its alloys. Such files, with deeply cut curved teeth, about 10 teeth per inch, are the best general purpose files. They remove metal rapidly, without the teeth loading, and produce a smooth finish. The long angle lathe file is also excellent for filing aluminum, especially for fine work. Files of this type generally have a pitch of about 14 to 20 teeth per inch with single cut teeth, cut at an angle of about 45-55°. This side rake angle causes the files to cut freely and helps to drive the cuttings from the teeth.

Ordinary files with single cut fine teeth do not work well on aluminum, and those with double cut teeth, whether fine or coarse, are no better because the teeth load with cuttings.

Grinding Wheels—Good results are obtained with commercial silicon carbide grinding wheels. The advice of the supplier should be obtained in selecting the proper grade of each commercial make of wheel.

Once a grinding wheel has been selected, there are three variables which affect the quality of a finish, namely, wheel speed, work speed, and grinding compound. A solution of soluble cutting oil and water works well as a grinding compound. It is important that the fine grindings of aluminum be strained from the compound before re-using, in order to prevent deep scratches on the finished surface. Wheel speeds of about 6,000 f.p.m. have given good results, but both wheel and work speeds can best be set by the experienced operator according to his own good judgment.

Cutting Speeds and Feeds—Wide ranges for cutting speeds and feeds may be used in machining aluminum and its alloys. The particular values for speed and feed are usually dependent on the character of the work, the type of tool, the lubricant, and the machine on which the work is done. Generally, aluminum can be machined to best advantage by using comparatively high speeds and fine to medium feeds; usually the finer the feed, the higher the speed should be.

A considerable amount of heat may be generated with tools which produce a tightly curled chip, and this may necessitate using a slower speed to prevent overheating of the tool and work. When using the slow speeds and coarser feeds, a

heavy cutting compound is preferred; this applies particularly to tapping operations. An increase in the amount of metal removed from the stock in a given time may often be accomplished by increasing the speed rather than the feed when using the tools described.

When using heavy, coarse-feed cuts in engine lathe work, a common occurrence with aluminum, as with most other metals, is the excessive friction set up on the lathe centers because of the expansion of the metal with rise in temperature. Ball or roller bearing tail stock lathe centers assist in decreasing this trouble.

Cutting Lubricants—Some of the alloys of aluminum have been machined successfully without any lubricant or cutting compound, using tools of the form described, but in order to get the best results, some form of lubricant is desirable. Kerosene oil will often serve, but usually it works better when mixed with pure lard oil. A satisfactory mixture for general use will be obtained by using equal parts of kerosene and lard oil. For heavy cuts and slow feeds such as in roughing work or tapping, pure lard oil has been found to give satisfactory results. For milling, sawing, and drilling, the soluble cutting oils are satisfactory and more economical than the kerosene or kerosene and lard oil lubricants. A continuous and copious supply of lubricant should be fed to the tool, in order to produce the best results. Cutting compounds of paraffin oil, such as are used in machining brass, may be found unsatisfactory for machining many of the aluminum alloys.

Part II

Automatic Screw-Machine Practice

Stock—The heat treated aluminum alloy, 17S-T, (nominal composition: 4% copper, 0.5% manganese, 0.5% magnesium), has been used almost exclusively for screw machine stock, but a recently developed alloy, 11S-T3 (nominal composition: 5.5% copper, 0.5% lead, 0.5% bismuth) is supplementing it in many applications. The latter alloy is well suited because its chips are small. Both alloys have similar cutting characteristics in respect to surface speed, lubricants, and types of tools used, but the free machining alloy has greater flexibility in respect to tool angles and tool feeds.

Drills—Standard twist drills are satisfactory for shallow holes, but for deep holes it is preferable to use straight fluted drills or twist drills with less twist, which have larger flutes to provide greater chip clearance. The flutes should be polished to offer freer passage for the chips.

For deep drilling, the drill must be withdrawn from the hole for chip removal and for lubrication of the point. It is safe practice to drill to a depth of four times the drill diameter on the first entrance, one and one-half to two times the diameter on the second entrance and three-fourths to one times the diameter on the third entrance.

Form and Cut-off Tools—Form and cut-off tools need not have top rake for the free machining alloy. For the other alloy a top rake of 5° is advantageous for penetration of the material and production of a smooth finish. In all cases, a side clearance of $\frac{1}{2}^{\circ}$ will aid in producing a smooth finish. Front clearance angles are determined by the design of the screw machine and the tools, and the angles generally used in screw machine practice are satisfactory for the aluminum alloys.

The side pressure of the form cutting tool, when used without support for the work, will spring the stock and break it off if the ratio of the formed length to the smallest diameter is too great. The limit for this ratio is $2\frac{1}{4}$ for the free machining alloy and $2\frac{1}{2}$ for the other alloy.

Box Tools—Box tool holders are designed so that the tool is usually set with a clearance angle of 8° but for some roughing tools this angle may be greater. The angle of the cutting edge with respect to the tool shank should, of course, correspond to the clearance angle so that the edge of the blade is parallel to the axis of the work. The cutting edge may be ground square with the tool shank, or with a slight rake angle, for the free machining alloy. For the other alloy, a small groove or "hook" is ground just behind the cutting edge in order to make a thin cutting edge and to provide considerable rake. This makes the tool cut more freely and forms the chips into helical coils, which are guided out of the holder and away from the work. For long, heavy cuts the feeding cams may be notched to provide an interrupted feed to break the cuttings.

Threading Tools—Taps with "hook" as supplied by the maker may be used, but it is important that they be the ground thread type, with smoothly polished flutes to allow freer exit of the chips. Thread chasers should be provided with 15-25° top rake or "hook". Taps and chasers should be tapered or chamfered at least for one thread at the leading end of the tool so they will start more easily.

Surface Speed of Stock—Aluminum alloys can usually be machined using the maximum spindle speed available in all standard types of automatic screw machines, for turning, drilling, forming, and cutting off. They have been machined at 800 stock surface feet per minute, with no indication that such speed is excessive. How much this may be exceeded has not been determined. For threading and tapping operations, each type of machine has a suitable speed which is considered good practice for machining aluminum as well as all other materials. This speed is approximately one-third of that used for other operations.

Table I
Approximate Feeds for Standard Tools for Machining
the Free Machining Aluminum Alloys—11S-T3

Tool	Cut Width or Depth, in.	Dia. of Hole, in.	Feed per Revolution, in.
Box Tools One chip finishing.. . . .	$\frac{1}{16}$	.....	0.012
	$\frac{1}{8}$	.....	0.010
	$\frac{3}{16}$	.....	0.008
	$\frac{1}{2}$	.....	0.008
	$\frac{3}{4}$	.....	0.006
Center Drills.....	.....	Under $\frac{1}{8}$	0.004
	.....	$\frac{1}{8}$ and over	0.008
Cut-off Tools Circular.....	$\frac{3}{16}$ - $\frac{1}{8}$	.....	0.0035
	$\frac{1}{2}$ - $\frac{3}{8}$	.....	0.003
Drills.....	.....	$\frac{1}{16}$	0.004
	.....	$\frac{1}{8}$	0.007
	.....	$\frac{3}{16}$	0.010
	.....	$\frac{1}{2}$	0.012
	.....	$\frac{3}{4}$	0.014
	.....	$\frac{1}{2}$	0.015
	.....	$\frac{3}{4}$	0.016
	.....	$\frac{1}{2}$	0.017
	.....	$\frac{3}{4}$	0.017
	.....	$\frac{1}{2}$	0.017
Form Tools	$\frac{1}{16}$ - $\frac{1}{4}$	.....	0.002
	$\frac{3}{16}$ - $\frac{1}{2}$	.....	0.0012-0.0015
	$\frac{5}{16}$ - $\frac{3}{4}$	.....	0.001
	1	.....	0.001
Reamers	{ 0.003-0.004	Under $\frac{1}{8}$	0.007-0.010
	{ 0.004-0.008	$\frac{1}{8}$ and over	0.010

The lighter weight of aluminum, about one-third that of other commonly used metals, is an advantage when using high spindle speeds. Its lower inertia causes less wear on the spindles, belts and motors, especially when quick changes in speed are involved.

Tool Feeds—Tool feeds vary with cutting conditions, as well as with requirements of tolerance and finish. The feeds shown in Table I for the free machining alloy are approximate and may have to be altered to meet different situations. In some cases, the same feeds may be used for the screw machine alloy that is not free machining, but generally they should be about 15% less.

Cutting Compounds—Cutting compounds which are used for other metals are generally suitable for the aluminum alloys. A cutting compound that produces satisfactory results consists of paraffin oil, to which 5-10% of lard oil is added.

Spinning of Aluminum

By L. J. Weber*

The forming of aluminum to useful shapes is commonly done by means of draw presses, hammering and spinning, or combinations of these methods. Spinning can be used only for shaping round and oval symmetrical articles. The equipment consists of a lathe, spinning chucks, and spinning tools. For small production the cost per piece is lower when produced by spinning than by other methods of forming.

The aluminum best suited for spinning is commercially pure aluminum in the annealed condition. Usually the shape can be spun without an intermediate anneal. If greater strength is desired in the finished article an aluminum alloy containing 1.25% manganese can be used. This alloy strain hardens more rapidly than the commercially pure aluminum, so more chucks may be necessary and on deep items an intermediate anneal may have to be used. In case annealing is necessary a fast method of heating such as immersion in a molten salt bath should be used in order to avoid grain growth. The temperature may vary between 650 and 750°F. and the time from 30 seconds to several minutes, depending on the thickness of the metal. A welding torch may be used on large items. A simple method for determining the correct temperature is to heat the metal until it will scorch a pine stick.

The drive on the lathe headstock should provide speeds of 1200, 1800, and 2400 r.p.m. The higher speeds are for spinning small items and thin sheet while the lower speed is for large items and thick sheet.

The chucks may be made of wood, cast iron or steel depending on the number of pieces to be made and the desired finish. Hardened steel chucks with a high polish produce the best surface finish.

The approximate reduction per chuck for different shaped shells is illustrated in Fig. 1. In case the items have reentrant angles a sectional chuck is necessary as otherwise it could not be removed from the spun article. Great care must be used to have the sections fit perfectly or else the offset at the joint will be impressed on the spun article.

At times the articles are such that a roll instead of a sectional chuck can be used. The roll has the contour desired in the finished shell. It is held against the aluminum to be spun by an offset spindle. This method has the advantage over the sectional chuck in that it increases production by eliminating the assembling and disassembling of the sectional chuck. It has the disadvantage that the spinning can not be done for some distance from the bottom as this is the space occupied by the back block. It also requires that the opening in the finished article be large enough to permit the entire mechanism to

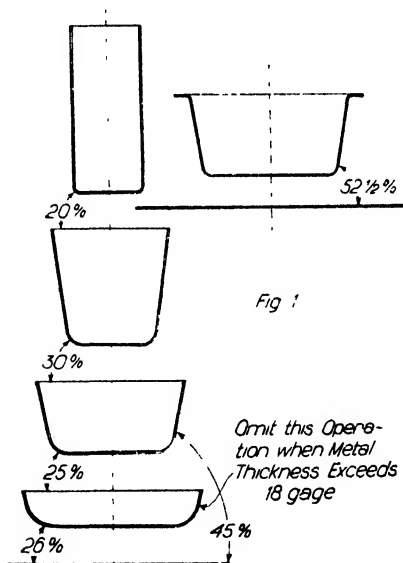


Fig. 1--Reductions per spinning operation.

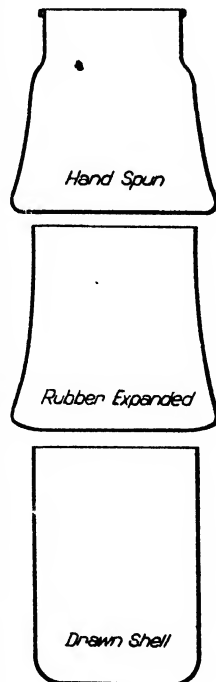


Fig. 2

Fig. 2--Sequence of operations for roll spinning.

*The Aluminum Cooking Utensil Co., New Kensington, Pa.

be removed readily. In order to avoid spinning to the bottom of the article, drawn shells may be formed at the bottom by bulging and the top spun to the required shape using a roll. The sequence of operations for a percolator made in this way is shown in Fig. 2.

Hickory sticks are usually used for the breakdown of the circles, then steel forming tools are used. Alloy steels intended for wear resisting applications may be used but satisfactory tools can be made from carbon steels (1.1% carbon).

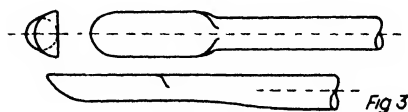


Fig. 3—Hand spinning tools.

The shape of the tool depends on the shape that is to be produced as well as on the preference of the operator. A tool with a flat surface on one side and half round on the other made from $\frac{3}{4}$ in. dia. rod is suitable for most work. Such a tool is illustrated in Fig. 3.

The lubricant used for spinning may be cylinder oil, roll neck grease or soap depending on the thickness of metal and the extent to which the metal is to be deformed. Thick metal and the more complicated shapes require the heavier lubricants.

In case the spinning is done on drawn shells, care must be exercised to avoid die scratches or similar surface defects. These will act as stress raisers and in some applications may cause cracking.

The flow of aluminum during spinning is regulated in the same way as for other metals. The sequence in spinning necessary to keep the metal under control is illustrated in Fig. 4. If the flare is too large excess thinning will occur while if it is too small the shell will buckle.

Commercial production experience has shown that to produce a wall thickness of 18 gage (B. & S.) in the finished work, the original circle should be 16 gage. This amount of thinning is considerably less than is ordinarily encountered when spinning copper or brass. If the amount of reduction is much more than two gages difficulty may be encountered because of fractures. The use of several chucks aids to prevent thinning of the metal and at the same time prevents the formation of buckles.

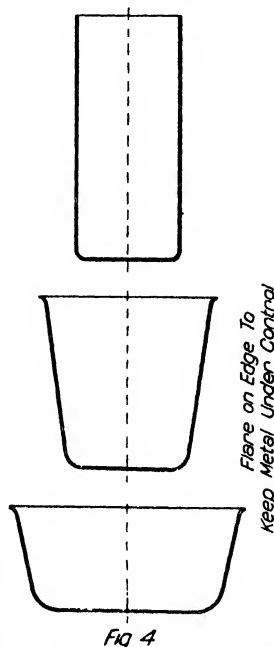


Fig. 4—Flare on edge to keep metal under control.

Protection of Aluminum and Its Alloys Against Corrosion

By W. L. Fink*

There is a widespread belief that aluminum and its alloys need no protection against corrosion. There are, however, conditions under which protection is necessary to maintain a satisfactory appearance and to preserve the metal. The conditions under which it is necessary to protect aluminum come under two general classifications—those which damage or prevent the formation and repair of the protective oxide coating, and those conditions which set up electrolytic cells.

Aluminum is inherently a very reactive metal, and it is resistant to corrosion only because it is protected by a very thin oxide film which forms spontaneously in air. Obviously, erosion or abrasion which constantly removes this protective surface film and exposes underlying reactive metal, will greatly accelerate corrosion. (This is not to be confused with periodic cleaning, which is beneficial.) Moreover, solutions which are sufficiently acid or alkaline either dissolve the film or weaken it to such an extent that corrosion occurs. Also, environments free from water and/or oxygen prevent the formation and repair of oxide coatings and thus accelerate the attack.

Since aluminum is anodic to most other metals, the aluminum will suffer electrolytic attack if it is exposed to an electrolyte while in contact with heavy metals such as copper, tin, and lead, which are cathodic to aluminum. A similar condition develops when salts of such heavy metals are in the solution contacting the aluminum. The metallic ions are reduced to the metal by the aluminum at certain points over the surface, thus forming minute electrolytic cells which may result in relatively deep pits. Appreciably less than one part per million of copper or tin in the solution will thus greatly accelerate the pitting of aluminum.

Electrolytic cells can also be set up by variations in the concentration of the solutions in contact with the metal. For example, a layer of dirt, thermal insulation, or similar absorbent material will hold solutions in contact with the aluminum and, at areas of good contact, will shield the aluminum from oxygen. The areas thus shielded will be anodic to the adjacent surfaces and will corrode electrolytically. Crevices in joints will give rise to similar cells.

Design and Maintenance—The most elementary way to protect aluminum is to avoid the causes of corrosion which have just been mentioned or to minimize their effect by careful design and use. Designs which avoid contacts between dissimilar metals, insure adequate drainage and ventilation, and facilitate inspection and cleaning, will aid greatly in minimizing corrosive attack. Dissimilar metals can be insulated and the crevices sealed with nonhygroscopic insulation. Sisalkraft paper, rubber, synthetic rubber, and fabrics impregnated with synthetic resin varnish or marine glue are suitable for such use. Contamination by harmful heavy metal salts can often be avoided by making, storing, and transporting the material in aluminum, or in suitably painted or enameled containers.

Periodic cleaning will destroy the electrolytic cells caused by dirt or reduced heavy metals. The type of cleaner to be used varies with the conditions. For removing heavy metals, an abrasive cleaner such as steel wool, is satisfactory. For removing dirt and maintaining the appearance of architectural parts, a liquid wax is a satisfactory cleaner. A thin layer of wax is left on the surface which facilitates subsequent cleaning. Uninhibited alkaline cleaners should be avoided or used with caution, because they attack aluminum.

Solutions which attack aluminum because they are too alkaline, too acid, or contain chlorides and heavy metal salts, can frequently be inhibited by the addition of small amounts of sodium silicate, sodium chromate or certain colloids. Alkaline cleaners containing sodium carbonate or trisodium phosphate, can usually be inhibited by the use of N or GC grades† of sodium silicate. Corrosion by water which is recirculated as in air conditioning systems and which has picked up acid (CO_2 and SO_2) and heavy metals, can be inhibited by the addition of sodium chromate. The addition of a little water to anhydrous organic liquids will frequently greatly reduce the rate of reaction.

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†Philadelphia Quartz Co., designations.

It is often possible to eliminate local electrolytic cells and make the entire surface equipotential by making the aluminum parts cathodic either by applying an external current or by connecting the aluminum to a more anodic metal, such as zinc. This is the procedure which has long been followed to prevent the corrosion of steel boat hulls adjacent to bronze propellers and fittings and to protect pipe lines.

When care in design and use is inadequate or is too expensive, and where the use of inhibitors is impossible, the aluminum alloys may be protected from the corroding media by suitable coatings. These coatings will be considered under three headings: Oxide coatings, metallic coatings and paint coatings.

Oxide Coatings—Since it is the natural oxide film on aluminum which makes it corrosion resistant, a method of securing better protection is to improve the oxide film. This can be done by boiling aluminum and its alloys in certain chemicals such as solutions of chromates and carbonates. The processes of this type known as Alrok* produce oxide films affording substantial protection.

More protective oxide coatings can be formed on aluminum by making the article the anode in a suitable electrolyte such as sulphuric acid, chromic acid, or oxalic acid. The coatings used to the greatest extent in this country, England, and Germany are described in references 1, 2, and 3.

Both the chemically produced and the anodically produced oxide film can be improved by after treatments known as sealing.¹ Dichromate solutions are among the most effective sealing solutions for enhancing the resistance to corrosion.

Although substantial protection is afforded by the oxide coatings in many environments, they do not afford perfect protection against all corrosive environments. A collection of dirt on an anodically coated surface exposed to an industrial or sea coast atmosphere will cause local break down of the coatings and pitting of the metal. In order to maintain an excellent appearance, it is therefore necessary to keep the surfaces clean. A liquid wax (such as Johnson's liquid wax) is one of the most satisfactory cleaners for this purpose. The film of wax left from one cleaning facilitates the next.

Metallic Coatings—Metallic coatings can be divided into two classes: those which are anodic to the aluminum alloy on which they are applied, and those which are cathodic. The protection afforded by the latter is purely mechanical. As soon as the coating is perforated at any point, the coating actually accelerates the corrosion of the exposed base metal by electrochemical action. On the other hand, coatings which are anodic to the base metal afford electrolytic protection after the coating is perforated. For this reason, coatings which are anodic are much more protective under severe corrosive conditions.

The most satisfactory of the metallic coatings are aluminum or aluminum alloys which are anodic to the base metal and fabricated integrally with it. The best known of these alloys are Alclad* 17S-T* and Alclad 24S-T. The outstanding protection afforded is illustrated by the fact that 14 gage (0.064 in.) tensile specimens of Alclad 17S-T have been exposed for 8 years to the continuous spray of the 20% sodium chloride solution at room temperature without suffering any measurable loss in tensile strength.

On rolled shapes, castings, and assemblies which can not readily be made as clad products, aluminum, aluminum alloys, zinc and cadmium may be applied in the form of a sprayed coating.² There are on the market several guns for applying such coatings. Careful preparation of the surface, as by grit blasting, is necessary in order to obtain satisfactory adherence of the coating. Moreover, sprayed coatings are porous so that it is necessary that the alloy used in the coating be anodic to the underlying metal. However, when the coating metal is suitably selected and properly applied, excellent protection is afforded. Sprayed coatings of aluminum have completely protected aluminum-copper and aluminum-silicon cast alloys against a 20% salt spray for 4 years.

Metallic coatings can also be applied to aluminum by electroplating.¹ Nickel and chromium have been used extensively and offer adequate protection if conditions are not too severe. However, both of these metals are cathodic to aluminum and, therefore, do not offer the electrolytic protection against corrosion which is afforded by zinc or cadmium.

*Registered Trade Mark, Aluminum Co. of America.

Paint Coatings—The most widely used coatings are paint coatings.¹ For best results, the surface of the aluminum should be given a suitable preparation for painting, an inhibitive primer should be used, and the top coats should be highly impermeable to moisture.

The best surface treatments are those which render the surface passive or chemically inert. Of these, the anodic coating is outstanding. It is widely used for aircraft parts² where section thicknesses are relatively small and low factors of safety are used so that little corrosion can be tolerated. Oxide coatings formed by the chemical dip method also furnish good surfaces for painting. Another good method for preparing the surface is the use of phosphoric acid solutions. There are a number available on the market.

The best inhibitive primers are zinc chromate primers such as those covered by the Navy Aeronautical specifications P27b. The zinc chromate in the primer acts as a corrosion inhibitor which maintains the passivity of the aluminum surface and prevents reaction with water or solutions which diffuse through the paint film.

An excellent paint for the top coats is aluminum paint made with a synthetic resin vehicle. This paint is highly impervious, and the metallic film which is formed by leafing of the aluminum bronze powder protects the vehicle from ultra-violet light, thus prolonging its useful life.

The above painting procedure is recommended for severe corrosive conditions. For less severe exposures a variety of materials are satisfactory.¹ Aluminum paint or other specially designed primers may be used. Primers containing lead compounds should not be used on aluminum. Some of the finishing coats may be oil base paints, long oil varnish enamels, and pyroxylin lacquers. It is important with the pyroxylin lacquers to select a primer which is compatible with the finishing coats.

Many of the processes described in the above article are covered by United States letters Patent.

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Low Melting Alloys

By Kent R. Van Horn*

General—The expression "low melting metal" is generally applied to alloys having a melting point or solidification range below the melting point of pure tin, 449°F. (231.9°C.). The low melting or fusible alloys usually consist of binary, ternary, and quaternary mixtures of bismuth, cadmium, lead, tin, and in some instances a quintary alloy with mercury.

Since Charpy's¹ constitutional studies in 1898, the metals of the low melting group (bismuth, cadmium, lead, and tin) have been thought to form simple eutectiferous systems, that is, the presence of intermetallic compounds or solid solutions was not observed. Recently, limited solid solubilities have been discovered in some of the binary systems which, however, would not affect the commercial applications of the alloys.

Metallic alloys which are completely molten at temperatures appreciably lower than the melting points of the component metals have long been recognized. It is known that a binary eutectic has a lower melting point than either of the constituent elements, and that the further addition of one or more low melting metals may form a ternary or polynary eutectic with a still lower melting point.

A striking example of the lowering of the melting point of the component metals is illustrated by the bismuth-lead system. Bismuth melts at 519.8°F. (271°C.), lead at 621°F. (327.5°C.), and the resulting eutectic at 255.2°F. (124°C.). The six binary eutectic temperatures of the low melting metals range from the Bi-Pb eutectic at 255.2°F. (124°C.) to the Cd-Pb eutectic at 478.4°F. (248°C.). The addition of a third component, either cadmium or tin to the binary Bi-Pb eutectic decreases the melting point to the ternary Bi-Cd-Pb eutectic at 196.7°F. (91.5°C.) or the Bi-Pb-Sn eutectic at 204.8°F. (96°C.). Parravano² with the aid of three-dimensional diagrams established the composition of the quaternary eutectic to be bismuth 49.5, lead 27.27, tin 13.13, and cadmium 10.10%, melting at 158°F. (70°C.). Budgen³, with apparently sensitive thermal equipment, determined the freezing point of this eutectic to be 149.9°F. (65.5°C.). Consequently, 149.9°F. was generally considered to be the lowest temperature at which the quaternary mixture of the fusible metals remains molten. Recently, Thompson⁴ and Smith and Walker⁵ confirmed Parravano's value of the freezing point (which was selected for the accompanying compilation). The melting points, however, of the low melting alloys can be lowered even to room temperature by the further addition of mercury. The introduction of 16% mercury to mixtures approximating the quaternary eutectic, that is, Wood's and Lichtenberg's alloys, decreases the temperature of complete solidification to 131°F. (55°C.). Low melting alloys can be obtained in a pasty condition at room temperature by the addition of about 50% mercury.

Composition and Melting Points—Table I is a list of the low melting alloys of commercial purity. Alloys prepared from high purity metals would, of course, have a higher melting point or range. The temperatures of the melting points were obtained from the literature references included in this article, and may be subject to inaccuracies. A number of the alloys were thought to possess definite melting points at the time of publication, but have later been proved to soften and gradually liquefy over a solidification range which may or may not be appreciable. The temperature of the melting range, when present, would be useful, but authentic data are not yet available. Smith and Walker⁵ are methodically procuring this information. Also the determination of the temperature of a eutectic, having a sharp melting point under equilibrium conditions, may be subject to under-cooling phenomena and consequent variable results.

Uses of Low Melting Alloys—Low melting alloys have a wide variety of practical applications. Perhaps the chief use is in soldering operations where the lead-tin alloys constitute the majority of the soft solders employed. Improved solders are also obtained by the replacement of tin by small quantities of cadmium. Bismuth is sometimes partially substituted for tin, which produces a soft solder that has the capacity to wet copper and brass. Rose's and Newton's mixtures are alloys of the bismuth-lead-tin class used as soft solder in the pewter trade. An extraordinary solder application is due to the ability of certain fusible alloys, especially Wood's,¹⁷

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Table I
Low Melting Alloys

Melting Point °F.	°C.	Composition, %					Name
		Bi	Cd	Pb	Sn	Hg	
140	60	53.5	....	17	19	10.5	Anatomical Alloy
154.4	68	50	12.5	25	12.5	....	Wood's Alloy ^a
154.4	68	50.1	10	26.6	13.3	....	Lipowitz's Alloy ^b
158	70	49.5	10.10	27.27	13.13	....	Quaternary Eutectic Alloy
158	70	45.3	12.3	17.9	24.5	....	Very Fusible Alloy
(Approx.)							
158	70	44.5	....	30	16.5	5-10	Fusible Tea Spoons
159.8	71	38.4	15.4	30.8	15.4	....	Fusible Alloy
167	75	27.5	34.5	27.5	10	....
170.6	77	50	6.2	34.5	9.3	....
176	80	35.3	9.5	35.1	20.1	....
179.6	82	50	7.1	42.9	....	....
196.7	91.5	51.6	8.1	40.2	....	....	Ternary Eutectic Alloy
197.6	92	50	....	30	20	....	Onion's or Lichtenberg's Alloy for Fine Castings
199.4	93	50	....	25	25	....	D'Arcet's Alloy for Fine Castings
201.2	94	50	....	31.2	18.8	....	Newton's Alloy
203	95	50.1	16.6	....	33.3	....	Fusible Alloy
203	95	55.6	11.1	....	33.3	....	Fusible Alloy
203	95	50	25	....	25	....	Fusible Alloy
204.8	96	52.5	....	32	15.5	....	Ternary Eutectic Alloy
208.4	98	47	....	35.3	17.7 ^c	....
212	100	40	....	20	40	....
212	100	50	....	32.2	17.8	....
212	100	53.8	....	15.4	30.8 ^d	....	Alloy for Fine Castings ^d
212	100	50	....	12.5	37.5 ^e	....
212	100	59.4	....	14.8	25.8 ^f	....
212	100	57.2	....	17.8	25 ^h	....
212	100	53.5	....	20	26.5 ⁱ	....
212	100	50	....	40	10 ^k	....
212	100	50	....	28	22	....	Rose's Alloy ^l
217.4	103	53.9	20.2	....	25.9	....	Ternary Eutectic Alloy
221	105	48	....	28.5	14.5	9Sb	Matrix Alloy ^m
226.4	108	42.1	....	42.1	15.8	....
235.4	113	40	....	40	20	....	Bismuth Solder
242.6	117	36.5	....	36.5	27	....
253.4	123	33.3	....	33.3	33.3	....
255.2	124	55.5	....	44.5	....	....	Binary Eutectic Alloy
261	127	22.2	....	44.5	33.3	....
266	130	30.8	....	38.4	30.8	....
269.6	132	28.5	....	43	28.5	....
280.4	138	57	....	....	43	....	Binary Eutectic Alloy
287.6	142	....	18.2	30.6	51.2	....	Ternary Eutectic Alloy
289.4	143	21	....	42	37	....
291.2	144	20	....	40	40	....
291.2	144	60	40	....	....	....	Binary Eutectic Alloy
298.4	148	19	....	38	43	....
300.2	149	25	....	50	25	....
303.8	151	18.1	....	36.2	45.7	....
305.6	152	23.5	....	47	29.5	....
307.4	153	14.8	....	40.2	45	....
309.2	154	15.3	....	38.8	45.9	....
309.2	154	14	....	43	43	....
311	155	17.3	....	34.6	48.1	....
311	155	16	....	36	48	....
316.4	158	16.6	....	33.2	50.2	....
318.2	159	10.8	....	43.2	46	....
320	160	13.7	....	44.8	41.5	....
320	160	10.5	....	42	47.5	....
320	160	11.2	....	44.4	44.4	....
321.8	161	10.2	....	41	48.8	....
323.6	162	10	....	40	50	....
329	165	13.3	....	46.6	40.1	....
329	165	11.4	....	45.6	43	....
332.6	167	11.7	....	46.8	41.5	....
341.6	172	12.8	....	49	38.2	....
350.6	177	....	32	....	68	....	Binary Eutectic Alloy
352.4	178	12.5	....	50	37.5	....
361.4	183	....	....	38	62	....	Binary Eutectic Alloy
....	....	27.5	....	27.5	45	....	Bismuth Solder
....	....	25	....	25	50	....	Bismuth Solder
....	....	47.4	13.2	19.4	20	....	Guthrie's Alloy
....	....	27.2	....	59.2	13.6	....	Alloy for Fine Castings

^aTemp. also given as 149.9°F. (65.5°C.)^bTemp. also given as 149°F. (65°C.)^cSoftens and can be kneaded^dAlso given as melting at 205°F. (96.5°C.)^eSoftens at 212°F. (100°C.) without melting^fSoftens at 212°F. (100°C.), easily oxidized^gSoftens at 212°F. (100°C.)^hBecomes nearly fluid at 212°F. (100°C.)ⁱBecomes quite liquid at 212°F. (100°C.)^jBecomes soft, but does not melt^kBecomes very liquid at 212°F. (100°C.)^mSolidification range 221-248°F. (105-120°C.)

to wet glass. The glass is not affected in making seals and connections in glass apparatus, because the alloys melt at low temperatures.

Low melting alloys are employed in the manufacture of safety devices for fire extinguishers and sometimes in boiler and electrical installations. The melting of the fusible alloy head in a sprinkler causes the release of water pressure and the operation of the alarm system. Different low melting alloys can be selected, depending on the desired operating temperatures.

A number of the low melting alloys have excellent casting characteristics. Lipowitz's, Wood's and other alloys approaching the composition of the quaternary eutectic are used for castings, statuettes, and dental work. Lead-tin antimony, lead-zinc and lead-tin-bismuth alloys are employed for making foundry patterns. The Pb-Sn-Bi eutectic expands on cooling and is used for taking impressions that necessitate a faithful reproduction of the finest details. The expansion of the mixture is characteristic of other alloys containing over 50% bismuth metal, which, in the pure state, expands 3.42% on freezing. The addition of mercury to a ternary or quaternary alloy lowers the freezing range sufficiently to permit the reproduction of anatomical and botanical specimens such as leaves and flowers. The classical magic spoons which melt in warm water are examples of fusible alloys to which mercury has been added.

During the war, gasoline tanks¹⁸ of a complicated design were made by the electrodeposition of copper plate on a low melting alloy casting, which was subsequently removed by immersing in boiling water.

Low melting alloys such as Wood's and Lipowitz's are frequently used for mounting small or irregular specimens in physical testing and metallographic laboratories. The casting and removal of the low melting alloy at temperatures approximating 158°F. (70°C.) will not generally impair the final result.

Recently, antimony has been substituted for cadmium to obtain a higher strength in a mixture (Matrix Alloy) approximating the quaternary eutectic ratio of the low melting metals. Matrix Alloy is frequently employed to locate dies in die shoes, guide pins in die plates and punches in punch plates.

Constant temperature baths of low melting alloys are used in quenching, drawing, and annealing operations in the heat treatment of steel and nonferrous metals. A number of alloys with various solidification temperatures are now at the disposal of the metallurgist.

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Constitution of the Cadmium-Nickel Alloys

By Dr. Carl E. Swartz*

Very little information on the cadmium-nickel system is available. The diagram reproduced in Fig. 1 is a modification of the original work of Voss in 1908.

Up to 7 or 8% nickel, cadmium and nickel are completely miscible when in the molten condition. On cooling a eutectiferous system between cadmium and the intermetallic compound NiCd_7 is found to exist. This compound decomposes at 490°C . into a cadmium-rich liquid and a second intermetallic compound (of unknown composition) richer in nickel than NiCd_7 . The eutectic between cadmium and NiCd_7 is located at 0.25% nickel and melts at 318°C . The solid solubility of nickel in cadmium is nil. The dotted portions of the diagram have been located only approximately.

Extension of the diagram beyond the limits shown would necessitate working under pressures sufficient to suppress the vapor pressure of the cadmium existing at and above the high liquidus temperatures. It is doubtful as well whether these regions richer in nickel would be of more than academic interest because of the brittleness of the alloy.

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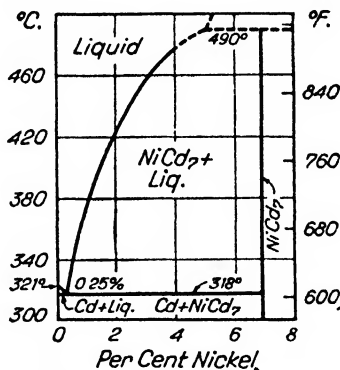


Fig. 1—Cadmium-Nickel Constitution Diagram.

*Metallurgist, Cleveland Graphite Bronze Co., Cleveland.

Properties of the Cadmium-Nickel Alloys (With Special Reference to Their Use as Bearing Liners)

By Dr. Carl E. Swartz*

General—The cadmium-nickel alloys are the only binary alloys of white metal used at the present time for linings in heavy-duty sliding-type bearings. Depending upon the type of service anticipated, the composition may run from approximately ½% nickel to 3%, the balance being cadmium.

The general casting characteristics of the alloys are very good. The physical properties are satisfactory. The compression strength, hardness and ductility are considered to be rather high. With the additional advantage of high fatigue resistance and elevated melting temperature, the system offers bearing alloys which have given and are giving a good account of themselves.

Structure—The alloys consist of a matrix of cadmium and the compound NiCd, analysing 0.25% Ni. When more than 0.25% Ni is present, excess of NiCd, forms grains in the shape of cubes or skeleton cubes. These have a hardness comparable to that of the average intermetallic compound, while the matrix is soft and ductile, but tough. The microhardness numbers (Bierbaum scratch hardness) for NiCd, is 260 and the matrix 55. The antimony-tin in babbitt is 204 and the matrix 61.

Bond—The alloys are the only white metal bearing alloys in commercial use which are directly bonded to iron and steel. That is, all other alloys have a different metal or alloy forming the bond, rather than forming it directly. In fact, the alloy is being used to bond other cadmium-base alloys to steel. The type of bond

itself is also unique, in that it is a solution-type rather than the type in which an intermetallic compound is formed with the iron. The nickel soaks into the iron surface slightly, after which the cadmium alloys with the nickel. As a result of this solid solution, the bond is much more ductile than ordinarily found and consequently appears to be much stronger.

Bonding is done in the manner conventional for other white metal alloys. The steel backing material after

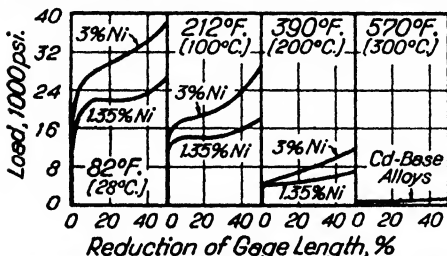


Fig. 1—Stress-strain relationship in compression for cadmium-nickel alloys.

Table I
Physical Properties of Cadmium-Nickel

	Temp., °C.			
	28	100	200	300
Tensile strength, psi.				
1.3% Ni., bal. Cd.....	16,400	10,500	3,300	600
3% Ni., bal. Cd.....	22,900	14,300	3,300	700
Yield strength, psi.				
1.3% Ni., bal. Cd.....	11,700	.....	.....	.....
3% Ni., bal. Cd.....	16,800	.....	.....	.....
Elongation in 2 in., %				
1.3% Ni., bal. Cd.....	19	36	111	162
3% Ni., bal. Cd.....	6	13	65	213
Reduction of area, %				
1.3% Ni., bal. Cd.....	43	52	76	78
3% Ni., bal. Cd.....	6	17	42	82
Brinell hardness number				
1.3% Ni., bal. Cd.....	33	22	6.6	1.8
3% Ni., bal. Cd.....	48	28	8.3	1.9
Rockwell hardness, B scale				
½ in. ball, 100 kg. load				
1.3% Ni., bal. Cd.....	65	.....	.....	.....
3% Ni., bal. Cd.....	84	.....	.....	.....
Fatigue strength, lb.				
1.3% Ni., bal. Cd.....	3,800	(20,000,000 reversals)		
Solidification range, °C.				
1.3% Ni., bal. Cd.....	395-318	.....	.....	.....
3% Ni., bal. Cd.....	457-318	.....	.....	.....
Coefficient of linear expansion				
1.3% Ni., bal. Cd.....		2.64 × 10 ⁻⁶ (60-140°C.)		

*Metallurgist, Cleveland Graphite Bronze Co., Cleveland.

fluxing is dipped in the cadmium-nickel alloy. After it is heated to the bath temperature, a thin layer of the cadmium-nickel alloy is deposited on the steel surface. The steel is then removed and while hot, cadmium-nickel of the same composition is cast onto it in the required thickness.

Physical Properties—Typical values of physical properties at various temperatures are shown in Table I. The stress-strain relationship in compression is given in Fig. 1. All values in both tension and compression were obtained at a testing speed of 0.05 in. per in. of gage length. Standard specimens of 2 in. gage length and 0.505 in. dia. were used for tension tests. Compression tests were made on specimens 1 in. dia. and 2 in. long.

Although all cadmium-base bearing alloys are susceptible to corrosion at elevated temperatures when lubricated under certain conditions, this property has not proved serious in most installations.

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Physical Constants of Calcium

By C. L. Mantell,* and Charles Hardy†

Introduction—In its commercial forms, calcium on freshly cut surfaces is white, approximating the color of silver. Fractured surfaces are more brilliant than steel. Upon exposure to the air, particularly in the presence of small quantities of moisture, the metal tarnishes with the formation of thin films of oxide which are bluish gray. These films are quite protective against further attack.

In contradistinction to sodium, calcium metal may be handled in a manner similar to magnesium and aluminum; that is, it may be touched and come in contact with the skin without danger. It can be machined in a lathe, turned into shapes, drilled, threaded, sawed, extruded, drawn into wire, pressed, and hammered into plates.

In its commercial forms, calcium is available as the direct product from the electric furnace, or as a remelted material, or as a sublimed material, in chips, slugs, rods, and sticks.

Atomic Weight—The atomic weight of calcium is 40.07 and its atomic number is 20. Its minimum number of isotopes is two, whose mass numbers in order of intensities of the mass spectrum lines show values of 40 and 44.¹

Crystal Form—From X-ray studies of calcium, A. W. Hull,² found that the crystals are in the cubic system with a face-centered cube lattice, with four atoms per elementary cube, a side of which is 5.56 Å and the smallest distance apart of the atoms 3.93 Å. W. L. Bragg³ gave a value of 1.70 Å for the atomic ratio.

Density—The specific gravity of calcium is 1.55. Impure material is slightly higher. According to Graf,⁴ the alpha phase in extruded calcium wire at 450°C. gives a specific gravity value of 1.48, while the beta phase at 480°C. gives a value of 1.52.

Compressibility—The compressibility or percentage change in volume with unit change in pressure of 1 megabar (0.987 atmospheres; 14,504 psi.) of calcium is given as⁵

Cubical, at 30°C., 0 atmosphere pressure.....	$\beta = 5.885 \times 10^{-6}$
Cubical, at 30°C., 11,600 atmosphere pressure.....	$\beta = 5.300 \times 10^{-6}$
Cubical, at 20°C., 99-493 atmosphere pressure.....	$\beta = 5.8 \times 10^{-6}$

$$\text{where } \beta = - \frac{1}{\text{vol. cm.}} \times \frac{dV_{\text{cc.}}}{dP_{\text{atm.}}}$$

T. W. Richards⁶ gives the average compressibility of calcium at 20°C. to be 5.7×10^{-6} between 100 and 500 megabars per sq.cm. Small amounts of carbides, chlorides, iron, and related materials increase the hardness of commercial calcium.

Thermal Expansivity—The thermal expansion of calcium is given⁷ as 0.000025 cm./cm./°C., while P. W. Bridgman⁸ found the coefficient of cubical expansion from 0-21°C. to be 0.000717. The linear coefficient of expansion of solid calcium between 0 and 300°C. is given as 220×10^{-7} .

Freezing Point—The freezing point of pure calcium is given in terms of a melting point at 810°C. W. Guertler and M. Pirani⁹ give a value of 809°C. According to recent investigations of Antropoff and Falk, the true melting point of nitride-free sublimed calcium is at a temperature of 851°C. $\pm 1^\circ$.

Specific Heat—The specific heat of calcium is 0.157 for the range from -185°-20°C., and 0.149 from 0°-100°C.

The heat of evaporation is given as 4.53×10^4 calories per mole.¹⁰

Entropy—The entropy of calcium is given by G. N. Lewis¹¹ as 10.64 for the solid and 36.71 for the vapor at 25°C. and one atmosphere pressure.

Boiling Point—The boiling point¹² of calcium is 1170°C. N. B. Pilling¹⁴ gives the following vapor pressures in millimeters of mercury, calculated from the rate of evaporation in a vacuum:

*Consulting Metallurgist, and †Pres., Hardy Metallurgical Co., New York.

At 300°C.	9.6 × 10 ⁻⁸
At 400°C.	4.2 × 10 ⁻⁸
At 500°C.	3.7 × 10 ⁻⁸
At 600°C.	1.2 × 10 ⁻⁸
At 700°C.	0.19
At 800°C.	1.8
At 900°C.	10.6
At 1000°C.	47.2

The latent heat of vaporization is 399 kilojoules per g. atom.¹¹

Thermal Conductivity—The thermal conductivity of calcium is low as compared to silver or copper, being of the same order as sodium and the alkali metals.

Electrical Resistance—In comparison with silver and copper, calcium is a poor conductor of electricity. It has an electrical resistance at 0°C. of 3.43 micro-ohms/cm.² according to J. H. Goodwin.¹² Its temperature coefficient of electrical resistance is 0.00457. In the case of metal containing 1.08% chlorine, P. H. Brace¹³ found an electrical resistance of 6.77 micro-ohms/cm.² at 22°C. The pressure coefficient of resistance of calcium increases with rising temperature, while the electrical resistance increases with rising temperature. The electrical conductivity of calcium at 20°C. is 45.1 on the basis of silver of the same area and length being taken as 100. The conductivity is exceeded only by that of silver, copper, gold, and aluminum. For the same length and weight of metal with calcium taken as 100, silver is 32.5.

Electrochemical Equivalent—Calcium occurs as a bivalent ion in all its compounds. The values in various units for the electrochemical equivalent (defined as the number of grams deposited per second by a current of one ampere) are given below.¹⁴

Mg. per coulomb	0.20762
Coulomb per mg.	4.81640
G. per ampere-hr.	0.74745
Ampere-hr. per g.	1.33789
Lb. per 1000 ampere-hr.	1.64784
Ampere-hr. per lb.	606.86

Electrolytic—According to the usual terminology, calcium is electronegative to elements it displaces in solution, and electropositive to those which displace it from solution. In simple solutions, calcium is electronegative to all of the base metals and the precious metals, and electropositive to the alkali metals. It shows an electrode potential of -2.76 volts.¹⁵

Mechanical Properties—Calcium shows a tensile strength of 8700 psi. Calcium metal is much harder than sodium, but softer than aluminum and magnesium. Its hardness characteristics are much closer to aluminum and magnesium than they are to sodium. Under 500 kg. load, sections machined out of the calcium cabbage as obtained from the furnace show a Brinell hardness of 17. Under the same conditions, sodium is so soft that measurement cannot be made, the hardness being under 1 on the Brinell scale. Pure aluminum, according to Edwards, Frary, and Jeffries,¹⁶ has a Brinell hardness of 25; while magnesium, according to the volume on magnesium published in 1923 by the American Magnesium Corporation, shows a Brinell hardness of 30, and measurements by the Dow Company on Dow magnesium show 32. On the Rockwell B scale, calcium in machined sections shows hardnesses from 36-40. On the Shore scleroscope, calcium shows hardnesses from 7-9 when the normal hammer is used, and 11-12 when the magnifying hammer is employed, as compared to values of 20-23 for magnesium.

Distilled calcium shows an elongation of 53%, while extruded wire gives 61%, 98.5% calcium 30.5%, and impure materials (94-96%) show no elongation.² The tensile strength of distilled calcium was 6,050 psi., its elastic limit 1,465 psi. With the loading speed of 4 mm. per minute, distilled calcium is more ductile than aluminum of 99.6% purity and less ductile than lead, but it has a greater elongation than both. The modulus of elasticity of distilled calcium varied between 32 × 10⁴ and 38 × 10⁴ psi. No creep was observed on loading calcium at room temperature with less than 570 psi. Crushing tests showed complete recrystallization of calcium at 300°C. and above during deformation. The pressure required for deformation decreases with the temperature and has a sharp break at 440°C., which corresponds to beta-gamma transformation temperature. Gamma calcium deforms plastically under very small loads. Calcium wire could be easily extruded between 420 and 460°C. It had an elastic limit of 5,500 psi. and a tensile strength of 8,000 psi.

Chemical Properties—Calcium at elevated temperatures oxidizes readily. This action is exceedingly rapid at its melting point, 810°C ., so that the material cannot be cast by the usual foundry methods. When melted in the absence of air, oxidizing influences, or reactive gases, it can be cast into various shapes. Recently, melting and casting procedures employing protective fluxes have been worked out for the production of cast forms of the metal from the irregularly shaped cabbages separated from the furnace electrodes.

Calcium is more active chemically than its sister metals barium and strontium. Due to its low atomic weight, 40 lb. of calcium is equivalent in reducing power to 137 lb. of barium, a ratio of more than 3:1. It is much cheaper than barium and for chemical purposes is the most economical of the alkaline earth metals.

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The Copper Industry

By Wm. G. Schneider*

History—Copper, known to the Greeks as *chalkos* and to the Romans as *aes Cyprium* or metal of Cyprus, from which our name for the metal was derived, was certainly one of the first metals reduced to the service of mankind. Where it was first produced is not known. Many of the ancient peoples used it and according to Prof. Gowland,¹ the Chaldeans had developed the art of working it to a high degree as early as 4500 B.C. According to the same author, the mines of the Sinai Peninsula were systematically worked as early as 3733 B.C. and probably much before that time. Cyprus yielded copper to the Egyptians 3000 B.C. and from Egypt the use of copper and bronze spread north through Palestine into Europe.

In America copper was used by the pre-Columbian peoples and by the Indians long before the arrival of Europeans. The native metal, especially that from the Lake Superior region, was widely distributed first by the glaciers and later through trade. According to Rickard,² who has recently reviewed the matter, it is doubtful if the Indians did much, if any, mining prior to the arrival of the white man. He credits Cuba with the first mine, opened in Santiago province in 1534, and notes the discovery of copper in Massachusetts in 1632. According to Rickard, mining began at Simsbury, Conn., in 1709, and in New Jersey some time before 1719. After an abortive attempt to mine the Lake Superior deposits, made in 1771 by Alexander Henry and Alexander Baxter, these ores remained untouched until 1846 when, following the explorations of Douglas Houghton and inspired by his enthusiasm, the Cliff mine was opened.

Copper seems to have been used first for ornament, and later for tools and arms. Discovery of the hardening effect of tin produced bronze which gave various peoples in succession important advantages in war. When, where, and how brass was discovered is not known, but the early and long used method of preparation was one of direct reduction from a mixture of copper or some of its ores and calamine (zinc carbonate). It was only in 1781 that Emerson invented the process of direct fusion of the metals.

The copper, brass, and bronze industries which were well established in Roman times, passed into eclipse during the Dark Ages, but came to the front again after 900 A.D. At the time of the discovery of America the arts of manufacture were well understood and came to us from Europe. According to Rickard the manufacture of pins from native copper by Yorkshire wire drawers was started at Lynn, Mass., in 1666 by Nathaniel Robinson, and brass is reported to have been cast in the foundry of John Winthrop in the same town two years before. Both brass and copper kettles were hammered out at Philadelphia as early as 1725. By 1750 Waterbury, Conn. had an establishment where knee and shoe buckles were made, watches repaired and imported brass buttons sold. Brass sheet rolling was first done at Waterbury in 1802, since which date Connecticut has continued to be the center of American brass manufacture.³

Early American production was based mainly upon scrap and imported materials. While persistent search was made elsewhere and various small mines were opened, it was not until after the development of the Lake Superior district that an adequate domestic supply of metal became available. These mines yielded nearly 6,000,000 lb. of copper in the first decade. Following the extensive development of this region the mines of Mont., Ariz., Utah, and Nev., each in turn, became important. Other states producing smaller amounts were N. M., Cal., Tenn., Colo., Idaho, and Alaska.

Occurrence—The average copper content of igneous rocks has been estimated by F. W. Clark at 0.010%. The metal content of copper ores of the United States for 1929 averaged 1.41% copper, 0.0067 oz. of gold, and 0.262 oz. of silver per ton. The value of the gold and silver was estimated to equal 28 cents per ton of copper ore. Jullihn⁴ reviewed the development of the technology of copper production and showed how it has permitted the working of leaner ore without increasing the cost per pound of copper.

More than 95% of all copper produced is obtained from sulphide, oxide, carbonate, silicate, sulphate minerals contained in copper ores. The sulphides are by far the most important with the others following in the order given.

*The American Brass Co., New York.

Extraction and Refining—After mining, concentrating and smelting, the blister copper is electrolytically refined and then cast into commercial shapes which may have a purity of 99.95% copper. In this process, the valuable metals consisting mainly of gold and silver are recovered and impurities removed. Copper is also recovered from its ores by direct leaching, electrolytically depositing the metal from the resulting solutions, and then casting into commercial shapes, such as wire bars, ingots and ingot bars, cakes, and billets. Copper from the refinery is also available as cathode and shot. Various grades of copper are furnished such as Electrolytic, Lake (from northern Michigan) Oxygen free, Deoxidized, Phosphorized, and Casting.

Production of Copper—The figures of the American Bureau of Metal Statistics show the following production in tons of 2000 lb.:

Year	United States	World
1929	1,028,348	2,118,209
1930	710,690	1,734,745
1931	524,831	1,487,992
1932	255,509	998,103
1933	233,649	1,146,260
1934	240,099	1,395,825
1935	380,100	1,608,857
1936	614,971	1,836,480

Principal Products—Copper is used as such in the form of wire, sheet and strip, rod, tube, anodes, castings and for alloying purposes. The copper used for fabrication meets the specifications of the A.S.T.M. which require a copper content of at least 99.900% with contained silver being counted as copper. Aside from the products of copper mentioned above it is furnished in fabricated form or as castings alloyed or mixed with other metals such as zinc, tin, nickel, silicon, aluminum, manganese, iron, beryllium, cadmium, chromium, lead and others. The principal alloys obtainable in various fabricated form such as sheet or strip, pipe or tube, rod or wire, extruded shapes, are classed mainly as muntz metal, yellow brass, cartridge brass, low brass, rich low or red brass, silicon brass, commercial bronze, gliding metal, Tobin bronze, naval brass, manganese bronze, phosphor bronze, silicon bronze, aluminum bronze, nickel silver, and cupro nickel. Castings of various other compositions are also obtainable, made up of copper and the metals mentioned above.

Uses—Copper and its alloys generally speaking may be worked and fabricated by the usual metal working processes such as rolling, extruding, drawing, stamping, spinning, forging, casting and die casting. Copper or its alloys may be welded by various methods, soldered and brazed.

Copper has the highest electrical conductivity, 100%, of all of the commercial metals. On a strength basis its conductivity is more than 200% of that of aluminum. Copper is the metal used most extensively by the electrical industry where conductivity is involved.

Copper also is the best conductor of heat among the commercial metals. Because of this property it or its alloys are used for heat exchange purposes, cooking utensils, radiators and for heat dissipating equipment.

Copper and its alloys have excellent corrosion resisting qualities where exposed to all types of atmospheric and potable water conditions. Therefore, they are most suitable and extensively used in the building industry for roofing and flashings, gutters, leaders, termite shields, screening, water and drainage pipes and tubes, heating lines, hardware, lighting fixtures, windows and sash, ornamental effects, store fronts and for wires and other items too numerous to mention.

Copper and its alloys exposed to oxidizing conditions soon take on a beautiful green patina which when once formed prevents further action. The longevity of copper roofs may be attributed to the fact that the patina protects the underlying metal. Aside from atmospheric conditions copper and its alloys are used in chemical plants, underground and under many other varied conditions where because of their corrosion resisting properties the service rendered is satisfactory and economical.

Copper and its alloys have a wide range of physical properties. Tensile strengths varying from 30,000 psi. for soft copper up to 200,000 psi. for the heat

treated copper-beryllium alloy are obtainable with other physical properties fluctuating depending on alloy composition, temper, and heat treatment.

Statistics—Table I compiled by the American Bureau of Metal Statistics estimates the use of copper either as such or in the form of its alloys.

Table I
Estimated Use of Copper in the United States
(In tons of 2,000 lb.)

Purpose	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936
Electrical mfres. (a).....	196,500	213,000	261,000	221,000	162,000	90,000	90,000	101,000	128,000	164,000
Telephones and telegraphs	93,000	119,000	164,000	122,000	70,000	27,000	18,000	18,000	18,000	26,000
Light and power lines (b).....	103,000	115,000	127,000	130,000	85,000	49,000	33,000	36,000	55,500	72,000
Wire cloth.....	5,400	7,100	9,000	9,200	4,900	4,200	5,000	4,600	5,600	6,500
Other rod and wire.....	76,050	87,100	106,200	93,700	55,000	30,000	46,000	40,000	48,000	90,000
Ammunition	4,600	8,200	6,900	5,100	5,000	3,900	10,500	13,500	13,700	11,900
Automobiles (c).....	100,800	127,400	138,200	87,000	61,600	32,300	49,000	63,000	95,000	108,000
Buildings (e).....	52,800	62,000	69,000	50,000	45,000	29,000	36,000	36,000	49,000	71,000
Castings, n.e.s. (d).....	67,200	72,500	79,500	55,400	38,000	27,000	38,000	36,000	36,000	39,000
Clocks and watches.....	5,000	4,600	4,300	2,600	2,000	1,500	2,800	2,200	2,400	3,400
Coinage	850	800	1,200	850	100	100	100	900	1,500	2,000
Copper-bearing steel.....	1,600	1,600	2,600	1,900	1,200	800	1,500	2,100	2,300	3,900
Fire-fighting apparatus..	2,500	2,300	2,400	1,700	1,300	1,000	1,100	1,000	1,200	1,300
Radiators, heating.....	850	1,100	2,100	3,000	1,700	1,000	2,400	1,000	1,100	2,000
Radio receiving sets.....	4,500	8,400	15,500	13,000	10,000	7,000	11,500	12,500	16,000	24,000
Railway equipment (f)...	8,000	6,000	9,600	8,800	1,800	700	800	2,100	1,800	4,000
Refrigerators (h).....	15,800	13,800	17,200	16,000	13,000	9,000	11,400	15,700	15,400	15,000
Shipbuilding (h).....	6,000	1,600	2,400	5,000	3,200	2,100	1,800	3,200	1,100	5,000
Washing machines (h)...	3,800	4,200	4,500	1,200	1,600	1,500	1,000	1,400	1,300	1,500
Water heaters, household	3,000	2,600	2,300	1,800	1,400	1,000	1,500	1,500	1,500	1,500
Air conditioning (g)(h).....	.....	.....	.....	.....	.....	.....	.....	3,800	4,800	6,400
Other uses.....	53,800	65,800	70,000	57,000	40,000	27,300	40,000	42,000	46,000	59,000
Mfres. for export.....	57,400	66,600	74,900	71,100	48,200	22,600	15,600	25,500	29,500	31,600
Total	862,450	990,700	1,159,800	956,150	650,000	368,000	415,000	463,000	574,700	749,000
Use in pounds per person	14.59	16.53	19.08	15.52	10.43	5.90	6.60	7.31	9.01	11.66

(a) Generators, motors, electric locomotives, switchboards, light bulbs, etc. (b) Transmission and distribution wire and bus bars; accounting only for the public utility companies. (c) Does not include starter, generator, and ignition equipment. (d) Bearings, bushings, lubricators, valves and fittings. (e) Excludes electrical work. (f) Includes air conditioning beginning with 1933. (g) Other than railway. (h) Exclusive of electrical equipment.

Use of Copper in the United States by Percentage

Purpose	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936
Electrical manufactures.....	22.09	22.78	21.50	22.50	23.11	24.91	24.46	21.69	21.81	22.27	21.90
Telephones and telegraphs...	11.43	10.78	12.01	14.14	12.76	10.77	7.33	4.34	3.89	3.13	3.47
Light and power lines.....	13.41	11.94	11.61	10.95	13.60	13.08	13.32	7.95	7.78	9.66	9.61
Other wire.....	9.72	9.45	9.51	9.94	10.76	9.21	9.29	12.29	9.63	9.33	12.89
Automobiles	11.48	11.69	12.86	11.92	9.10	9.48	8.78	11.81	13.61	16.53	14.42
Buildings	5.52	6.12	6.26	5.09	5.23	6.92	7.88	8.67	7.78	8.53	9.48
Refrigerators, automatic.....	1.65	1.83	1.39	1.48	1.57	2.00	2.45	2.75	3.39	2.68	2.00
Other uses.....	19.11	18.76	18.14	17.52	16.43	16.21	20.35	26.74	26.60	22.74	22.01
Manufactures for export	5.59	6.65	6.72	6.46	7.44	7.42	6.14	3.76	5.51	5.13	4.22
Totals	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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Constitution of Copper-Aluminum Alloys

By H. C. Jennison* and Cyril Stanley Smith†

Because of their industrial importance the constitution of the alloys of copper and aluminum rich in copper has been studied repeatedly. The work of Stockdale,¹ which is a model of accurate work by the classic methods of thermal analysis and microscopic examination of quenched samples, includes brief references to the earlier work and established the diagram for the copper-rich alloys which has not been appreciably changed by more recent work. His work forms the basis of the diagram which is shown in Fig. 1.

The liquidus slopes gradually down from the melting point of copper to a eutectic point at 8.4% aluminum where the liquid solidifies at a fixed temperature (1031°C.) to a mixture of alpha containing 7.4% and beta containing 8.8% aluminum. The liquidus and solidus are close together through the entire alpha and beta range and the alloys are therefore free from segregation on casting, an important commercial consideration. Rising from the eutectic point the liquidus reaches a flat maximum above the pure beta phase at 1048°C. and about 12.5% aluminum and then falls once more toward the region of the gamma phase.

The limit of solubility of aluminum in the alpha phase is 7.4% at 1031°C. and increases lineally to about 9.5% at 570°C. Stockdale believed the solubility limit to be 9.8% at temperatures of 530°C. and below, but the solubility 9.5% at a temperature of 570°C. is in agreement with his experimental results and it is unlikely that

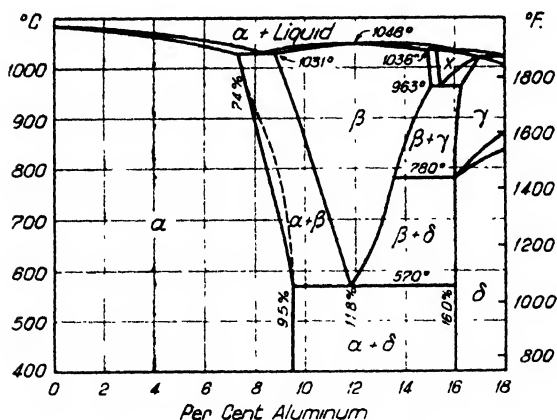


Fig. 1—Copper-aluminum constitution diagram.

the solubility would continue to increase below the eutectoid temperature which is now known to be higher than he assumed. Obinata and Wassermann studied the location of the alpha boundary by X-ray methods and gave the results shown as a dotted line in Fig. 1. They state that there is no change of solubility below 650°C. and consider the solubility limit at the eutectoid point and below to be 9.43%. This is in good agreement with Stockdale's figure at 570°C. Inasmuch as X-ray studies on alloys quenched from high temperatures are somewhat uncertain (on account of partial transformation) particularly when the diffusion rate is high, it is felt that preference

should be given to Stockdale's results above the eutectoid temperature.

It should be pointed out that in other similar systems, notably the copper-tin system, when the rate of transformation has been accelerated by cold working, the solubility at low temperatures has been found to be much less than previously suspected. It is not unlikely that the same situation exists in the system at present under consideration. Obinata's and Wassermann's alloys were slowly cooled and annealed for long periods without any intermediate cold working.

The feature of greatest interest is the eutectoidal decomposition of beta which takes place at a temperature in the neighborhood of 570°C. and at a composition of 11.8-11.9% aluminum.²

The beta phase cannot be retained by quenching but gives rise to a structure bearing microscopic resemblance to martensite in steel. Although the mechanism of transformation has been studied repeatedly it is still somewhat obscure, but it can be said that there are at least three distinct transitional phases involved, each with a structure derived from one of the three equilibrium phases.⁴ It is owing to the presence of these phases that the mechanical properties of the alloys are susceptible to improvement by heat treatment.

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The recent work by Dowson⁵ indicates a greater complexity than suspected by Stockdale in the alloys from 15-17% aluminum above 963°C. On the basis of microscopic, thermal and dilatometric work, Dowson introduced the phase which, following him, is called X in Fig. 1. It decomposes eutectoidally at 963°C. to beta and gamma. This X phase is formed peritectically at 1036°C. and it gives rise to gamma by another peritectic reaction with liquid at 1022°C. Gamma itself gives rise to delta at a temperature between 780-873°C. depending on composition although these two phases are very similar to each other and no structural difference is to be found by the examination of quenched samples.

The arrangement of the gamma + delta field has been studied by Stockdale⁶ and particularly by Hisatsune.⁷ The works of Tazaki⁸ and Matsuyama⁹ are both in Japanese and difficult of access, and therefore have not been critically reviewed for this article. There seems, however, to be nothing in either diagram inconsistent with the interpretation shown in Fig. 1.

The crystal structures of the phases under consideration have been studied by a number of workers. Obinata and Wassermann¹⁰ showed that the lattice parameter of the face centered cubic alpha phase increases linearly with increasing aluminum content from 3.608 Å at 0% up to 3.658 at 19.6 atomic per cent aluminum, the limit of solubility. The beta phase¹¹ is body centered cubic with random atomic arrangement and a cube edge of 2.94 Å at 580°C. A phase beta₂ of the same lattice but with an ordered arrangement of atoms exists transitionally below the eutectoid point while the beta¹ phase which forms at lower temperatures bears some relation to alpha. The delta phase¹² has, in common with many other alloys with an electron-atom ratio of 21:13 or 1.62, the complex cubic structure typified by gamma brass. This contains 52 atoms in a unit cube of parameter increasing from 8.865-8.700 Å as the aluminum increases from 16.5-19.0 weight per cent but beyond that point (with no metallographic distinction) a slightly different structure appears in which progressively fewer atoms are associated with the unit cube, which departs slightly from true cubic symmetry and shrinks somewhat in size.

See page 1222 for a discussion of the aluminum end of this diagram.

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- In addition to the above special references the book by C. Panseri "Metallografia Dei Bronzi D'Alluminio," Milano, 1937, should be consulted for discussion of the constitution, properties, fabrication and uses of aluminum bronzes.

Constitution of the Copper-Beryllium Alloys

By H. C. Jennison* and H. F. Silliman†

Lebeau^{1,2} appears to have been the first to study the alloys of beryllium and copper. He prepared a series of alloys containing up to 10% beryllium and recorded their color, malleability, tarnish resistance, and solubility in acid.

The first diagram of thermal constitution was published by Oesterheld³ in 1916. Bassett⁴ and Corson,⁵ in papers dealing with the mechanical properties of beryllium-copper alloys, later noted that the limit of alpha solubility above 650°C. is at a higher beryllium concentration than shown by Oesterheld. Corson also suggested that the solidus and liquidus over the beta field needed modification.

Masing^{6,7} and his associates redetermined the diagram in 1928 and 1929, and made several important changes in the form and position of the boundaries of the alpha and beta fields. In 1932, Borchers⁸ published a diagram which agrees closely with that of Masing except for a modification of the solidus and liquidus over the beta field.

Tanimura and Wassermann⁹ investigated the alpha field by X-ray methods and found evidence that the alpha-alpha plus beta boundary is at a slightly lower beryllium concentration than shown by either Masing or Borchers.

In the diagram here reproduced the alpha phase boundary is drawn as a mean of the results of Masing, Borchers, and Tanimura and Wassermann.

As may be seen from the diagram, the solubility of beryllium in copper increases with temperature. Alloys containing up to about 2.4% beryllium retain a pure alpha structure when quenched from a suitable temperature above the alpha boundary. In this condition the alloys are malleable and ductile, and are capable of being wrought into a variety of forms. Upon reheating such material at temperatures between 250 and 400°C. precipitation of the gamma phase occurs, bringing about a noteworthy increase in the tensile strength, elastic limit, hardness, and related properties.

The alpha plus beta alloys also show precipitation hardening effects but brittleness increases rapidly with the percentage of the beta phase in the structure so that alloys containing more than 3% beryllium cannot be cold worked.

Alloys in the beta, beta plus gamma, gamma, and gamma plus delta fields are too hard for fabrication. Castings containing 4-11% beryllium respond to heat treatments analogous to those applied to steel and may find some uses where small, extremely hard articles are required.

Of the above alloys, those containing 0.6-11.2% beryllium have an alpha plus gamma structure at temperatures below 575°C. The form and distribution of the gamma phase in the microstructure may be varied widely by reheating (below

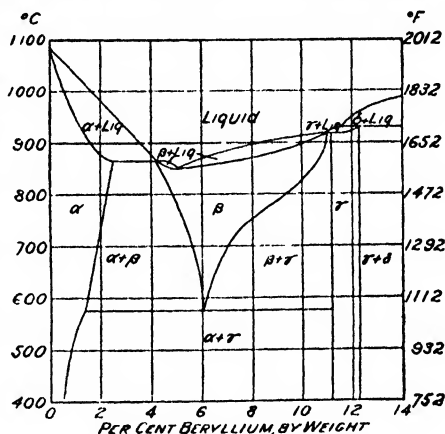


Fig. 1—Copper-Beryllium Constitution Diagram.

Precipitation Hardening of 2.15% Beryllium-Copper Alloy Sheet

	Quenched From 800°C.	Quenched From 800°C. Reheated 2 hr. 300°C.
Tensile strength, psi.....	70,000	175,000
Yield point, 0.75%, psi.....	31,000	134,000
Young's modulus, psi. x 10 ⁻⁶	18.0	18.9
Elongation, % in 2 in.....	45.0	6.3
Rockwell hardness.....	G69	G103
Brinell hardness.....	110	340

*Deceased. †American Brass Co., Waterbury, Conn.

575°C.) material previously quenched from temperatures near the melting range. The temperature and time of this reheating govern the precipitation and thus the resulting properties of the alloys. As an example, the preceding table gives some of the mechanical properties of an alloy containing 2.15% beryllium, first as quenched from 800°C. and then as reheated for 2 hr. at 300°C. after quenching from 800°C.

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Constitution of Copper-Cadmium Alloys

By Cyril Stanley Smith*

The alloys of copper and cadmium have not been subject to extensive investigation. Heycock and Neville¹ studied the molecular depression of copper on the freezing point of cadmium, and Sahmen² published a complete diagram in 1906. This showed the existence of compounds Cu_2Cd and Cu_3Cd , the first forming peritectically from copper and liquid, and the second forming directly from the liquid. Sahmen found a eutectic between these two compounds and another close to the cadmium end of the diagram between Cu_3Cd and cadmium.

In 1913 Bornemann and Wagenmann³ carried out an investigation on the electrical conductivity of the alloys in the solid and molten state and also determined the melting points and boiling points of a few of the alloys in the neighborhood of Cu_2Cd . Their results indicate unmistakably the existence of molecular association corresponding to the presence of the compound Cu_2Cd in the liquid state.

A careful examination of the equilibrium relations by Jenkins and Hanson⁴ gave the diagram shown in Fig. 1. This diagram differs from that of Sahmen principally in the introduction of a new constituent, gamma, which corresponds closely to the compound Cu_2Cd , but exists over a composition range of about 2% at 200°C. Sahmen supposed cadmium to be insoluble in solid copper, but Jenkins and Hanson introduced the alpha field, consisting of copper with a maximum of 2.7% cadmium in solid solution at all temperatures between 200°C. and the peritectic temperature, 549°C. The portion of the diagram from 45-75% cadmium is redrawn on a larger scale in Fig. 2, which shows more clearly the gamma field. The beta phase corresponds exactly to Sahmen's Cu_2Cd and has no appreciable variation in composition.

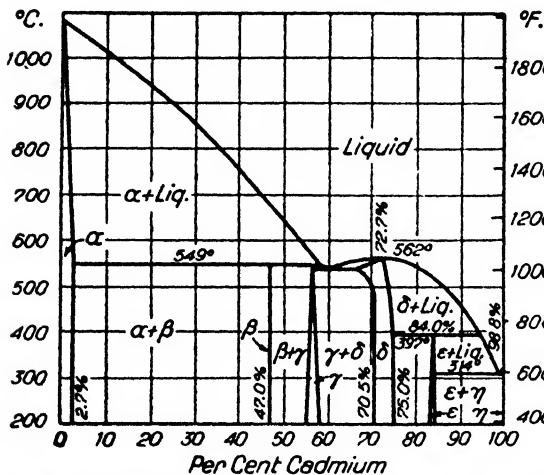


Fig. 1—Copper-cadmium constitution diagram (Jenkins and Hanson).

between 200°C. and the peritectic temperature, 549°C. The portion of the diagram from 45-75% cadmium is redrawn on a larger scale in Fig. 2, which shows more clearly the gamma field. The beta phase corresponds exactly to Sahmen's Cu_2Cd and has no appreciable variation in composition.

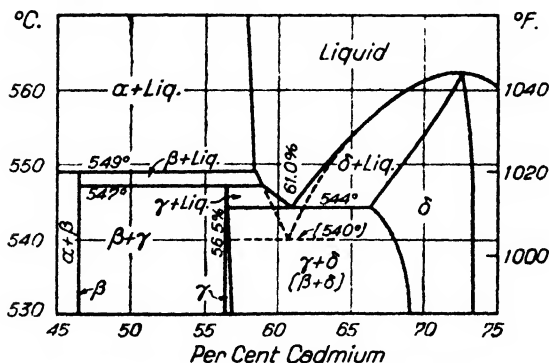


Fig. 2—Gamma field of copper-cadmium alloys.

The new gamma constituent of Jenkins, although the stable phase below 547°C., is not formed even with slow rates of cooling from the liquid state, but only after

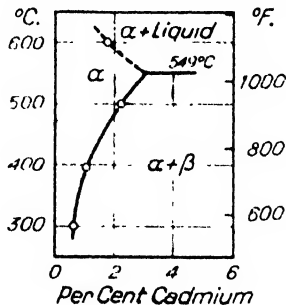


Fig. 3—Alpha phase boundary in the copper-cadmium system (Owen and Pickup).

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long annealing at temperatures near the highest at which it is stable. Under ordinary conditions the only constituents in cast alloys within this range of composition are beta and delta, which form a metastable eutectic at a temperature of 540°C., 4°C. lower than the freezing point of the stable gamma plus delta eutectic. The molten alloys containing above 25% cadmium have a high vapor pressure, and, although no actual determinations have been recorded, the boiling point curve at atmospheric pressure evidently comes close to the liquidus at this point.

Owen and Pickup⁷ have reexamined the alloys by X-rays but were unable to determine the crystal structure of the beta, gamma and epsilon phases by the powder method used. By measurements of the parameter of samples annealed for prolonged periods at various temperatures, they established the limit of the alpha phase to be 1.2, 1.0 and 0.5% cadmium at temperatures of 500, 400, and 300°C. respectively. Their results are plotted in Fig. 3. This sloping alpha boundary is much more probable and more in keeping with the properties of the alloys than the vertical line given by Jenkins and Hanson. The work of Pogodin, Mischeva and Kagan, according to an abstract,⁸ places the alpha boundary at 1.0% cadmium at room temperature increasing to 1.2% at 250°C., 1.6% at 400°C., 2.1% at 475°C., 2.5% at 525°C., and 2.8% at 550°C. These solubilities are higher than those reported by Owen and Pickup at low temperatures. It seems likely that the lower solubility of the latter investigators is more nearly correct.

Richards and Evans⁶ studied the resistivity, temperature coefficient of resistance, thermoelectric force, Hall coefficient, density and specific heat of a complete series of alloys. The curve for each of these properties showed a discontinuity at the phase boundaries according to the diagram of Jenkins and Hanson, with which they are in complete accord. The alloys were tested in the form of cast plates which were thoroughly annealed until no further change in conductivity took place. There was little change in conductivity on annealing save with the alloys containing 56-64% cadmium where the metastable beta plus delta eutectic in castings gives rise to the stable gamma form.

The crystal structure of most of the phases is unknown. The delta phase, which is shown to range around Cu_3Cd (73.92% cadmium) rather than Cu_2Cd (72.7% cadmium), was studied by Bradley and Gregory,⁹ who found it to be cubic of the gamma brass type. There are 48 atoms in the unit cube, which has a parameter of 9.635 Å, corresponding to a density of 9.0 g. per cc. Cu_3Cd differs from Ag_3Zn , Au_3Zn , and, by analogy, from Cu_3Zn , in the division of the copper atoms among the four groups of structurally equivalent positions in the lattice. In Cu_3Cd , 16 copper atoms are divided equally by two sets of positions, only one of which is occupied by copper in Cu_3Zn , while the remaining two structurally equivalent locations, containing 12 and 24 atoms respectively, seem to be occupied indiscriminately by a group of 4 copper and 32 cadmium atoms.

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Constitution of Copper-Chromium Alloys

By H. C. Jennison* and Cyril Stanley Smith†

The chromium-copper diagram has not been established with great accuracy. The commercially useful alloys contain less than 1% chromium and the only published data on this part of the system are those of Corson.¹

Studies of the complete diagram were made by Hindrichs² and Siedschlag.³ Both these investigators agree in showing a copper-rich eutectic at 1075-1076°C. and a two-liquid field existing above a monotectic horizontal at 1465-1468°C., but, whereas Hindrichs considers the two-liquid zone to extend from 1 or 2% up to more than 95% chromium, Siedschlag considers it to stretch from 37 or 38% chromium to 93% chromium. The latter figures seem to be more nearly correct. Beyond the monotectic point the liquidus rises rapidly to the melting point of chromium. The solubility of copper in chromium has not been determined, but is probably very small.

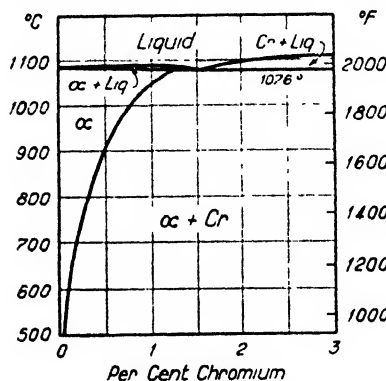


Fig. 1—Chromium-copper constitution diagram.

The melting point of the copper-rich eutectic can be stated with some certainty as being at 1076°C. The composition of the eutectic, however, is in doubt. Siedschlag stated that microscopically an alloy containing 1% chromium showed primary copper and one with 2% chromium contained primary chromium. There is no evidence to place the eutectic composition more exactly within these limits. In Fig. 1 it is arbitrarily shown as 1.5%.

The solid solubility of chromium in copper shown in Fig. 1 is that given by Corson. Without giving experimental details, he states that the solubility is 0.8% chromium at 1000°C., 0.5% at 900°C., 0.25% at 800°C., and 0.05-0.1% at 500°C. Extrapolation of the curve passing through these points indicates a solubility of about 1.25% at the 1076°C., the eutectic temperature.

There is some indication that these solubility figures are slightly high but in the absence of other determinations they must be accepted.

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Constitution of Copper-Lead Alloys

By G. C. Holder*

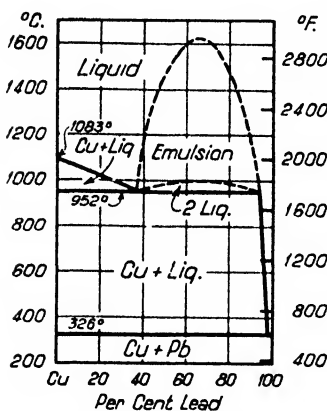
Copper and lead in the solid state are practically insoluble. The eutectic point of this series of alloys is near the lead boundary and contains 0.06% lead. This eutectic freezes at 326°C., which is 1°C. lower than lead; freezing point being 327°C.

On the horizontal line of the liquidus at 952°C., a three phase equilibrium monotectic reaction occurs, and the two conjugate liquid solutions contain about 7.5-62% copper respectively. According to W. Claus, 1600°C. is the maximum critical point for homogeneity in accordance with results obtained by electrical conductivity; and with fall in temperature, two distinct liquid layers start forming at 999°C.

Between 100 and 62% copper, the alloys form a homogeneous solution above the liquidus curve. Temperature gradient to the liquidus causes a separation of copper crystals from the mother liquor and continues until a concentration of 62% copper is reached. Further reduction of heat causes the second liquid layer to form as copper continues to crystallize. Because of the presence of three phases, this crystallization takes place at a constant temperature of 952°C.; and when the first liquid phase is exhausted, only the second phase remains with the frozen copper. A continued temperature fall produces further separation of copper until the eutectic point at 326°C. is reached and final solidification occurs. Alloys of less than eutectic concentration have a normal freezing procedure.

Copper and lead have similar face-centered crystal structure. X-ray diffraction of copper-lead alloys show no homogeneity as the line patterns of the two base metals are compared with the alloy and show no shift in line patterns; whereas, if a compound were formed or if a solid solution were present to any appreciable degree, a shift of line patterns would be in evidence.

In an alloy containing 15% lead, fair uniformity is obtained with moderate rate of cooling. The 30% lead alloy, chilled, is also fairly uniform, but beyond 30% lead the use of fluxes; such as, manganese, arsenic, nickel, and lithium, or combination of these fluxes with temperature control, are advantageous to reduce segregation. Almost any range of hardness can be produced; as for example, an alloy of 74% lead, 20% copper, 6% nickel, together with arsenic produces an alloy that has twice the hardness of lead, good ductility, and lead sweating temperature of about 900°F. (480°C.). Sulphur is also used, but produces a brittle product.



Constitution of copper-lead alloys.

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Constitution of Copper-Manganese Alloys

By Cyril Stanley Smith*

Although Valenciennes, Heusler, Moissan, and others made and examined copper-manganese alloys as early as 1870, the first attempt to determine the constitution of the series was by E. A. Lewis,¹ who found a marked minimum in the liquidus at 47% manganese which he interpreted as indicating a eutectic between solid solutions of copper with 5% manganese, and manganese with 20% copper respectively. S. Wologdine² criticized Lewis's work and himself suggested a diagram with a minimum melting point at 40% manganese and a maximum corresponding to a compound Mn₂Cu at 78% manganese. The existence of this compound has been negated by the work of subsequent investigators, and it is probable that Wologdine's alloys absorbed carbon in amounts sufficient to give the spurious arrests he observed in his thermal curves.

In 1908 the diagrams of Sahmen³ and Zemczuzny, Urasow and Rykowski⁴ were published, both of which showed a continuous series of solid solutions, the liquidus and solidus joining at a minimum point at 35% manganese and 866°C. (Sahmen) or 30.3% manganese and 868°C. (Zemczuzny). The diagrams agreed very closely on the copper-rich side of the minimum point. There was some difference between the liquidus temperatures on the manganese side of the diagram, but the principal discrepancy between the two diagrams lay in the solidus, which Sahmen showed as practically horizontal up to 70% manganese (in approximate agreement with Lewis) while Zemczuzny showed the solidus to rise close to the liquidus. Both investigators claimed that the alloys could be rendered microscopically homogeneous, and Zemczuzny's diagram seemed more in accordance with this, and was generally accepted until very recently.

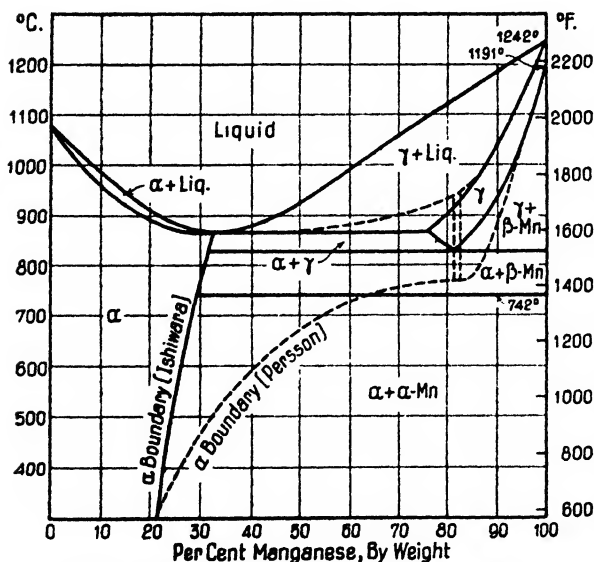


Fig. 1—Copper-Manganese Constitution Diagram.

ganese, and it became evident that the diagram needed reexamination. A diagram was then published by Ishiwara¹³ which outlined definitely the heterogeneous areas in the diagram, but later Persson and Ohman¹⁴ and Sekito¹⁵ showed that it is not impossible for copper and gamma manganese, stable at high temperatures, to be isomorphous, and Persson¹⁴ put forward the results of some X-ray determinations to prove that this was actually so.

When the constitution diagrams began to be critically examined in the light of crystal structure, it was apparent that the two metals manganese and copper, could not be isomorphous at all temperatures, for copper is face-centered cubic and the crystal structure of manganese in its low temperature modifications is far more complicated. Bain^{6,7} and Patterson⁸ found the manganese lines to appear on X-ray diffraction patterns of the alloys at 50-60% manganese, although Patterson found a change in the copper lattice even after it had presumably been rendered invariant by the appearance of manganese. Microscopic work by Corson¹² and by Smith¹³ placed the solubility limit at 800°C. at approximately 30% man-

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The diagram shown in Fig. 1 is slightly modified from that of Ishiwara. The liquidus is drawn as an average through the points of all investigators, as also is the solidus on the copper-rich side of the minimum melting point. The melting point and temperatures of the transformation of pure manganese are those given by Gayler,¹⁸ neglecting two points which do not seem to be accompanied by a change of crystal structure. Ishiwara placed the minimum point at about 34.5% and 850°C., but the higher temperature, 868°, has been adopted since the other investigators agree so well on this. The temperature of the gamma eutectoid is that of Ishiwara, 830°. The limit of the alpha phase drawn through Ishiwara's experimental points (confirmed by the single approximate points of Smith and Corson) intersects the liquidus and solidus at the minimum point, a condition that is thermodynamically possible only as the limiting case. Copper is soluble in the gamma form of manganese, stable between 1191°C. and the melting point, and depresses the transformation point to about 830° with 19% copper, where it decomposes by a eutectoid reaction to beta manganese and the alpha solid solution. Beta manganese later changes to alpha manganese at a temperature of about 742°. In the determination of the eutectoid temperature Ishiwara found that alloys, particularly those in the neighborhood of the eutectoid, were frequently homogeneous when they should have consisted of two phases. The reactions were extraordinarily slow and not always reproducible, rendering microscopic examination, or indeed studies of any kind, extremely difficult. The limits of the gamma phase at higher tem-

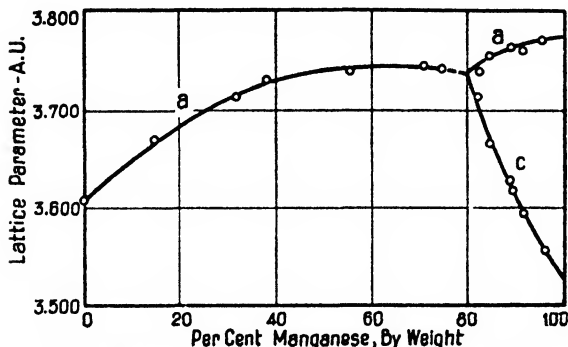


Fig. 2—Lattice Parameter of Copper-Manganese Alloys (Persson).

peratures (where it is in equilibrium with beta manganese or liquid) were easily determined by quenching experiments.

This diagram is by no means certainly established; not only is there some older microscopic evidence to show that all the alloys can be homogeneous under certain conditions, but also there is X-ray evidence to indicate that copper and gamma manganese may be isomorphous, since the face-centered tetragonal lattice of manganese may gradually change to that of copper, which can be regarded as face-centered tetragonal with an axial ratio of one. Persson¹⁹ from an X-ray study of alloys of extreme purity made from distilled manganese came to the conclusion that this was actually the case and suggested the diagram shown by dotted lines in Fig. 1.

Gayler¹⁸ found distilled manganese to melt at 1244°C. and to have transformations at 1191, 1024, 742, and 682°, but the work of Sekito²⁰ and Persson and Ohman²¹ makes it apparent that there are changes in crystal structure only at 742 and 1191°C. (Sekito gives 800 and 1100°) which corresponds to the change from alpha manganese to beta and from beta to gamma manganese. Alpha manganese has a complex body-centered cubic lattice, with 58 atoms in the unit cube, which measures 8.894 A.U.; beta is a modified simple cubic arrangement with 20 atoms in a unit cube measuring 6.300 A.U.; while gamma has the simplest structure of all, a face-centered tetragonal lattice: $a = 3.744$ A.U., $c = 3.526$ A.U., $c/a = 0.934$. A modification of manganese identical with gamma was obtained by electrolysis, although it was impossible to retain gamma by quenching from high temperatures and its structure was determined by quenching a series of copper-manganese alloys (which are stable on quenching) and extrapolating to 0% copper. The effect of dissolved copper on the structure of gamma manganese is to increase the axial ratio, and at 19% copper this becomes 1.0, the lattice then being identical with a face-centered cubic lattice. Sekito and Persson are in perfect agreement on this point. Further additions of copper to the alloy may go into solution, and since copper is itself face-centered cubic, the possibility of complete isomorphism is evident.

The lattice parameter of the entire series of alloys quenched from suitable temperatures is shown in Fig. 2, taken from the work of Persson.¹⁴ By comparing the parameter of alloys quenched from 400, 500, and 600°C. with this curve, Persson obtained the alpha boundary shown by the dotted line in Fig. 1. The curve in the most interesting portion of the diagram is, however, so extremely flat that high accuracy could not be attained. Indeed, Persson's values for the parameter beyond 40% copper are constant within ± 0.003 Å and the experimental results could be equally well satisfied by a sloping curve up to 40% manganese intersecting a horizontal straight line at this point. If this were really so, the solubility of manganese in copper would be about 40% and between 40 and 80% manganese there would coexist two phases of almost identical structure, possibly with a difference in the preferential location of the copper and manganese atoms in the gamma lattice. If copper and gamma manganese were truly isomorphous, it would seem that the axial ratio should vary continuously across the diagram rather than to change suddenly to 80%.

The results of Valentiner and Becker⁹ for the lattice parameter (which are in essential agreement with Persson except that they flatten at 3.75 instead at 3.73 Å), susceptibility and electrical resistivity are all open to the same interpretation. The data fall on fairly straight lines from about 50-80% manganese and could result from a two-phase zone just as well as from a solid solution series. The susceptibility reaches a marked maximum at about 25 atomic per cent manganese, probably due to an ordered structural arrangement. The value of the susceptibility is much higher at -188°C. than at room temperatures. The electrical resistivity at 20°C. according to Valentiner and Becker increases steadily from copper to gamma-manganese with a flattening in the curve in the range from 50-90% manganese. Schemtschushny and Petraschewitsch¹⁰ and others found a flat maximum in the curve of electrical resistance in the range 50-60% manganese and the hardness shows a similar maximum at 60-70% manganese. The thermoelectric force¹¹ and the crystal structure up to 20% manganese¹² agree with the proposed diagrams, indicating that the alloys in this range are homogeneous solid solutions.

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Constitution of Copper-Nickel Alloys

N. B. Pilling* and T. E. Kihlgren*

Copper and nickel crystallize with a face-centered cubic lattice, and their alloys form a very simple series with complete miscibility of copper and nickel both in the liquid and solid states. The diagram determined by Guertler and Tammann¹ has been closely confirmed by Tafel² and stands unquestioned.

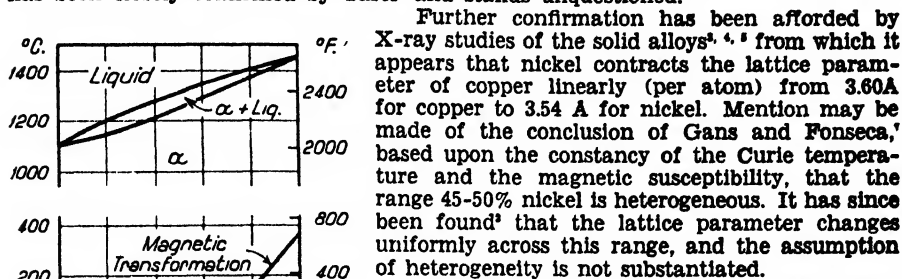


Fig. 1—Copper-nickel constitution diagram (Guertler and Tammann).

Further confirmation has been afforded by X-ray studies of the solid alloys^{3, 4, 5} from which it appears that nickel contracts the lattice parameter of copper linearly (per atom) from 3.60 Å for copper to 3.54 Å for nickel. Mention may be made of the conclusion of Gans and Fonseca,⁶ based upon the constancy of the Curie temperature and the magnetic susceptibility, that the range 45-50% nickel is heterogeneous. It has since been found⁷ that the lattice parameter changes uniformly across this range, and the assumption of heterogeneity is not substantiated.

The magnetic transformation of nickel, which is accompanied by no structural change, is depressed by copper to about room temperature at 68.5% nickel.^{1, 2} This transformation persists at sub-atmospheric temperatures and is reported to be about -170°C. at 50% nickel.^{1, 2}

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**These are the more important.

Constitution of Copper-Phosphorus Alloys

By H. L. Burghoff*

Except for the determination by Guillet in 1905 of the liquidus of alloys containing up to 15% phosphorus and the freezing point curve reported in 1906 by Hlorns and Tucker, the literature, prior to the work by Heyn and Bauer in 1907, contains only results of simple chemical studies of the phosphides of copper. The earlier investigators found several phosphides of which only the one with the formula Cu_3P is of commercial importance.

Several important experimental observations were made by Heyn and Bauer. Alloys higher than 15% by weight of phosphorus cannot be prepared by fusion, but

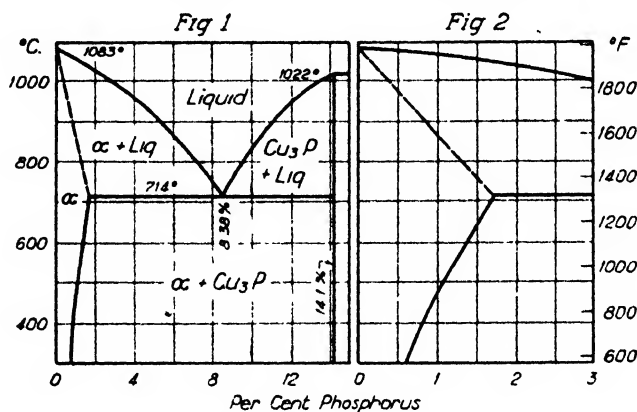


Fig. 1—Copper-phosphorus constitution diagram.

Fig. 2—Alpha phase boundary of the copper-phosphorus constitution diagram.

must be prepared by heating copper turnings with phosphorus at a lower temperature. Alloys richer in phosphorus are unstable at high temperatures and lose phosphorus, there tending to be a definite limiting value for each temperature. Thus at 1100°C. the saturation content is 14.1% phosphorus, which corresponds to the formula Cu_3P . In rapid heating and melting of phosphorus-rich alloys, as in casting into ingots, there is not sufficient time to reach the saturation limit of 14.1%, and thus the commercial ingot of 15% phosphorus is obtained.

The constitutional diagram for alloys of copper with phosphorus up to 15% is shown in Fig. 1. Heyn and Bauer found the eutectic at 8.27% phosphorus with a melting point of 707°C., this being confirmed in 1908 by Huntington and Desch. More recent work by Lindlie places the eutectic composition at 8.38% phosphorus and the eutectic temperature at 714°C. as shown in Fig. 1.

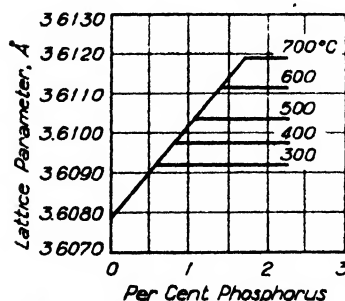


Fig. 3—Lattice parameters for copper-phosphorus alloys.

The compound Cu_3P , containing 14.1% phosphorus, melts at 1022°C. The alloys shown above 14.1% phosphorus are composed of crystals of Cu_3P and of a second phosphide, probably Cu_2P . No solubility of copper in Cu_3P has been observed.

Heyn and Bauer placed the solid solubility of phosphorus in copper at 0.175% on the basis of their microscopic observations of slowly cooled specimens. Hudson and Law, however, placed the limit at about 1% phosphorus upon finding that a phosphor copper containing 0.9% of phosphorus by weight had an almost homogeneous structure after annealing for 2 hr. at 690°C., or 4 hr. at 640°C. In 1930 Hanson, Archbutt, and Ford investigated the solid solubility of phosphorus in copper, and reported

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that the solubility decreased from approximately 1.2% phosphorus at 707°C. to approximately 0.5% at 300°C. Mertz and Mathewson have since established the alpha phase boundary in Fig. 1, and, on a more open scale, in Fig. 2, using X-ray methods and prolonged heat treatments of carefully homogenized material which assured equilibrium conditions. The lattice parameters determined by them are shown in Fig. 3.

In spite of the variable solubility of phosphorus in copper, capacity for precipitation hardening of copper-phosphorus alloys appears to be negligible. Hanson, Archbutt & Ford found that the Brinell hardness of quenched strip of an alloy containing 0.95% phosphorus was increased from 43 to 52 by heat treatment, but no increase in tensile strength was obtained.

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Constitution of Copper-Silicon Alloys

By Cyril Stanley Smith*

The early history of the alloys of copper and silicon, some of which were made and examined by chemists over a century ago, was given by Baraduc-Muller¹ and need not be further discussed here. Hansen² reproduces and discusses all diagrams published prior to 1936.

The earliest diagram was that of Rudolfi,³ which indicated the presence of a compound Cu_3Si forming a eutectic both with silicon and with a beta solid solution, the latter decomposing to a complex compound, Cu_5Si_4 , at 710°C .

The diagram of Sanfourche⁴ was more complex and showed the existence of five distinct solid solutions, two of which underwent polymorphic changes. The alpha limit was placed at 5% between room temperature and 731°C . and about 4.3% at 845°C .

Corson⁵ discarded all previous work as incorrect and suggested a diagram which is very simple, but which does not in any way explain the thermal observations of the earlier workers. His diagram was the first to show a sloping alpha boundary.

Matuyama⁶, by electrical resistivity measurements and thermal analysis, deduced a diagram which was not greatly different from that of Rudolfi. He showed the solubility of silicon in copper to be 5.9% at 800°C . and 4.9% at room temperatures. The beta solid solution was supposed to decompose at 795°C ., while the gamma phase was formed by a peritectoid reaction at 800°C . and underwent a polymorphic change to gamma at 738°C . His delta solid solution corresponded approximately to Cu_3Si , but had a variable composition.

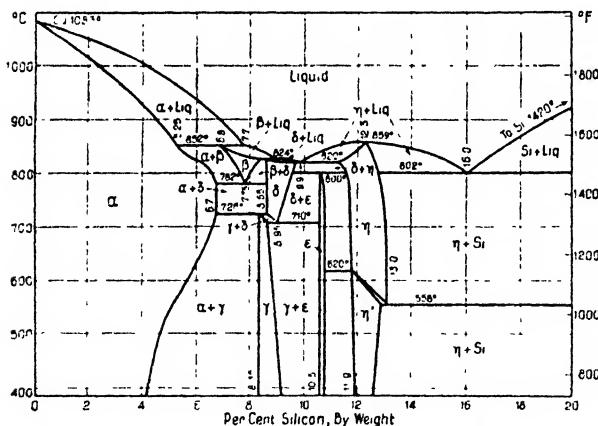


Fig. 1—Copper-silicon constitution diagram. See text for discussion of an additional phase not shown in this diagram existing at about 6% silicon and between 552 and 842°C .

change between 620 – 558°C . It forms a eutectic with silicon at 16.0% silicon and 802°C ., and with the delta solid solution at 9.9% silicon and 820°C .

Smith's diagram showed no horizontal at 800°C . and no phase between 9–12% silicon. Iokibe⁷ confirmed Matuyama's discovery of the horizontal at 800°C . and ascribed it to the formation by a peritectoid reaction of a phase containing 10.6–10.7% silicon, which is stable between room temperatures and 800° , but which does not form sufficiently rapidly to produce an arrest on cooling curves. By a study of the crystal structure of the alloys quenched from 550°C ., Arrhenius and Westgren⁸ independently discovered the same phase, but finding alloys quenched from 800° to be free from it, supposed it to decompose at 620°C ., corresponding to the heat evolution which had been attributed by Smith to a polymorphic transformation in the phase at 12% silicon. The break in the conductivity curves of Matuyama is so very definite that it seems probable that the higher temperature is

According to the diagram of Smith¹, the solubility of silicon in copper reaches its maximum value, $6.7 \pm 0.1\%$ silicon between 726 – 782°C . At 852°C ., the temperature of the peritectic formation of beta from liquid and alpha, the solubility is 5.25%, while below 726°C . the solubility decreases gradually to 4.0% silicon at 350°C . Beta decomposes at 782°C . to alpha and delta, while delta itself decomposes at 710°C . Gamma, which corresponds closely to the compound Cu_3Si , is formed by a peritectoid reaction at 726°C . The solid solution at about 12% silicon melts at 859°C . and suffers a polymorphic

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the correct one. This phase has been shown as forming at 800°C. in Fig. 1, which is believed to represent the most probable form of diagram. In accordance with the nomenclature of Arrhenius and Westgren, the new phase is called epsilon and the phase at 12% silicon (called epsilon by Smith) becomes eta. Except for this addition the diagram is essentially that of Smith but certain other points criticized by other workers should be noted.

Arrhenius and Westgren further modified Smith's diagram by moving the beta field to a lower silicon range and changing slightly the limits of the gamma and eta phases, but their experiments, made with a limited number of alloys and at only two temperatures, do not permit the phases to be outlined very accurately. Sautner¹⁸ was unable to find the epsilon phase and proposed a number of other changes in the diagram. Part of his diagram is reproduced in Fig. 3. He considered the gamma phase to extend up to the solidus at 815°C. but there is no evidence in the other papers on the system to support this, indeed, Arrhenius and Westgren reproduce X-ray powder photographs showing clearly the co-existence of beta and delta in samples quenched from 800°C.

Sanfourche and Smith supposed eta to undergo one polymorphic transformation. Iokibe found two transformations while Arrhenius and Westgren found no change in crystal structure from room temperature to the melting point.

On account of the importance of the alpha phase, the only one which possesses considerable ductility at room temperature, the part of the diagram up to 8% silicon is redrawn on a larger scale in Fig. 2. The alpha phase boundary shown in this as well as in Fig. 1 is that of Smith which was generally accepted until Von Schwartz²² stated that there was a new phase at the limit of the alpha. Sautner¹⁸ in a more detailed study introduced this phase in the diagram at about 6% silicon extending from 700-830°C., where it was supposed to melt peritectically at the same temperature as the beta phase—a thermodynamic impossibility. In the part of Sautner's diagram reproduced in Fig. 3 his phases have been renamed in accordance with Fig. 1 and 2 to avoid confusion and the new phase which he calls beta is here labeled "X." According to Sautner the alpha boundary runs between 5.1% at 700°C. and 4.9% silicon at 830°C. and decreases to 4.2% at 400°C. The new phase seems to be the same as that first noticed by Voce²³ in the ternary copper-silicon-manganese system. Isawa²⁴ has confirmed its existence röntgenographically but believes it to be stable at room temperatures.

The system is now (Nov. 1938) being reinvestigated in the writer's laboratory by microscopic and thermal methods. The beta peritectic remains at 852°C. The new phase has a wider range of existence than Sautner suspected. It forms from alpha and beta by a peritectoid reaction at 842°C. and contains 5.9% silicon at this temperature. The silicon-rich boundary of the phase is essentially the same as that shown for the limit of the alpha phase in Fig. 2 until at 552°C. and 5.2% silicon the phase decomposes to an alpha + gamma eutectoid. The alpha phase boundary slopes lineally from 5.30% at 842°C. to about 4.6% at 552°C. and about 3.8% at 400°C.

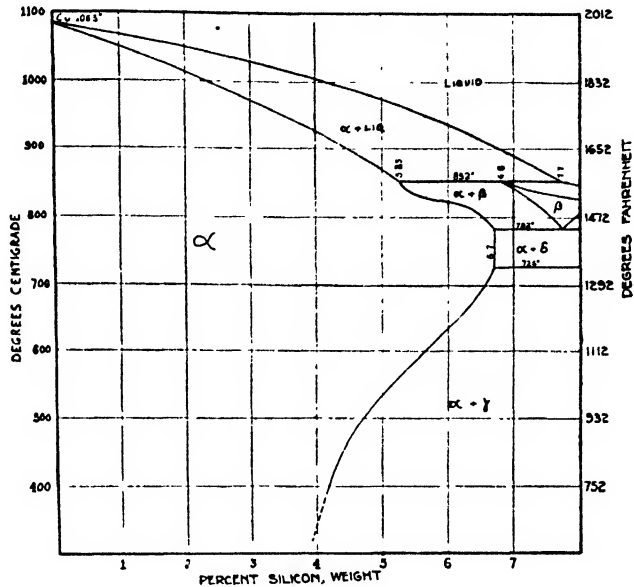


Fig. 2.—Copper-silicon constitution diagram up to 8% silicon. See text for discussion of additional phase containing about 6% silicon not shown in this diagram, and a new location of the alpha boundary.

Very unusual structures are observed in the two-phase region, for the alpha and "X" phases co-exist as fine twin-like lamellae and show no tendency to spheroidize on annealing.

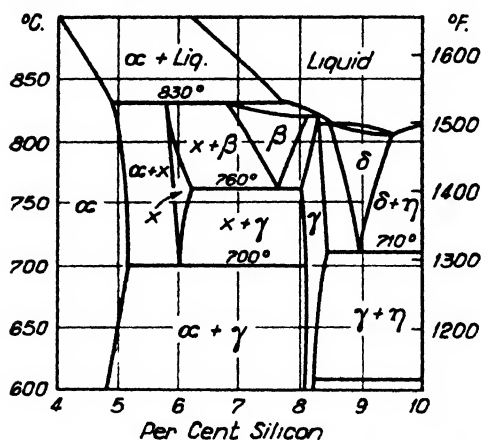


Fig. 3—Copper-silicon constitution diagram after Sautner.

Crystal Structure—The crystal structure of all the phases has been studied by Arrhenius and Westgren¹¹ and the alpha phase by Davey,⁸ Bain,⁹ and Kaiser and Barrett.¹² The last named investigators give the values in the table below for the parameter of the face-centered cubic lattice of the alpha solid solution quenched from 725°C. Sautner believes the structure of the new "X" phase at about 6% silicon to be hexagonal close packed, with $a_0 = 2.40$ Å and the unit cell containing 16 atoms of copper and silicon. This is manifestly impossible since such a cell is not large enough to contain even six copper atoms. Isawa²⁰ considers it to be hexagonal with $a = 2.552$ Å, $c/a = 1.628$. According to both Arrhenius and Westgren, and Sautner, the beta phase is hexagonal close packed in structure, $a_0 = 2.59$ Å $c/a = 1.633$.

The gamma phase is supposed by Arrhenius and Westgren to have the cubic structure typified by beta manganese, and contains 20 atoms in a unit cube of 6.21 Å edge. Silicon and copper must be interchangeable in the structure if this is so,

% Silicon	Lattice Parameter A. U.	% Silicon	Lattice Parameter A. U.
0	3.6078	5.02	3.6150
1.09	3.6103	5.91	(3.6151)
3.01	3.6128	6.36	(3.6157)

for no integral number of Cu₂Si groups can be fitted in the cell. The delta structure could not be determined but is apparently of a distorted gamma brass type.

The structure of the epsilon phase, first described by Arrhenius and Westgren as being cubic with 76 atoms (4 groups of Cu₂Si) in a cube measuring 9.694 Å edge, was later completely solved by Morral and Westgren²¹ who assigned the space group T_h² (I $\bar{4}$ 3d). Sautner did not find a homogeneous phase in this region but ascribed a similar structure to the eta phase at high temperatures.

Arrhenius and Westgren found that the eta phase had a diffraction pattern partly accounted for by a hexagonal structure derived from a body-centered cubic lattice of gamma brass type but this did not account for all lines. Sautner considers this to be a tetragonal body centered lattice, $a = 9.21$ Å, $c/a = 1.14$.

Silicon²² has a diamond cubic structure, 5.418 Å, parameter. Its melting point has recently been redetermined as 1410°C. for metal of from 99.89% purity,²³ and Gayler²⁴ has given the temperature of 1415°C. as the melting point of a sample containing 99.93% silicon.

Mehl and Barrett²⁵ have studied the mechanism of precipitation of the gamma phase from alpha. They find it forms in thin plates on an indeterminate family of planes of high indices, showing as many as twelve directions on a section.

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Constitution of Copper-Silver Alloys

By Cyril Stanley Smith*

The copper-silver system was one of the earliest to be examined by scientific methods. Roberts-Austen¹ determined the liquidus curve in 1875, while in 1897 Heycock and Neville² determined a diagram which has been changed but little by more recent researches. Levil,³ on account of the fact that an alloy of 72% silver solidified without segregation, supposed this alloy to be the compound Ag_2Cu , but later work has shown this to be a eutectic.

The liquidus curve has been determined by Heycock and Neville,² Friedrich and Leroux,⁴ Hirose,⁵ and Broniewski and Koslacz,⁶ all of whose results are in substantial agreement. Hirose's results on the silver-rich section of the liquidus are somewhat below those of Friedrich and Leroux, whose curves, agreeing closely with that of Heycock and Neville, are used in the composite diagram, Fig. 1. Friedrich and Leroux gave the eutectic temperature as 778°C. at 72% silver; Heycock and Neville, 779° at 71.9%; Hirose, 778° at 71.5%, and Broniewski and Koslacz, 779° at 71% silver. Roeser,⁷ with a view of establishing the eutectic temperature definitely so that it might be used as a secondary standard for the calibration of pyrometers (for which it is admirably suited) determined the temperature with great accuracy and stated it to be $779.4 \pm 0.1^\circ\text{C}$. Stockdale⁸ in a careful study of a number of eutectics gave the composition of that in the copper-silver system as 71.94% silver, which value is probably the most accurate that has been published.

The solid solubility limits have been determined by a number of observers, although with conflicting results. Friedrich and Leroux gave the composition of the saturated solutions as 1 and 94% silver respectively, while the results of the annealing experiments of Lepkowski⁹ were 6 and 95% silver at 750°C. The electrical resistance of the alloys has been determined, amongst others, by Kurnakow, Puschin and Senkowsky,¹⁰ whose curves indicate the solubility limits to be at 6.5 and 94.8% silver respectively, in alloys which were annealed and slowly cooled.

Silver-Rich Alloys—The observation of Fraenkel,¹¹ independently confirmed by both Norbury¹² and Leach and Chatfield,¹³ that sterling silver can be hardened by heat treatment proved that the solubility must change with temperature, and the investigations of Fraenkel and Schaller,¹⁴ Haas and Uno,¹⁵ Johanssen and Linde,¹⁶ Wienbaum,¹⁷ and Hansen¹⁸ confirm this. Fraenkel and Schaller worked principally with the 8% silver alloy, but they found that an alloy with only 2.84% copper could be age-hardened after long annealing at 280°C., and therefore the solubility is less than this amount. Johanssen and Linde determined the electrical conductivity of a number of alloys after annealing both for 90 hr., at 750°C. and 100 hr. at 350°C., followed by quenching. The breaks in their curves correspond to solubility limits at 8.2 and 93.8% silver respectively at 750°C., and 1.7 and 97.6% silver at 350°C. Hirose¹⁹ gives a complete diagram in which the solubility of silver in copper at the eutectic temperature is shown at about 5%, and of copper in silver at 6%, both solubilities decreasing rapidly to a negligible amount at 600°C. Broniewski found the solubility limits at 779° to be 6% and 93% silver. Moller by electrical conductivity determinations found the solubility of silver in copper to be 6% at 728°, decreasing to 3.9% at 529°C.

The work of Hansen¹⁸ was the first in which the solubility of copper in silver was determined with a high degree of accuracy. By microscopic examination of quenched and reannealed samples he found that the solubility of copper in silver was 9.0% at the eutectic temperature, decreasing to 1.7% at 300°C. By determining the

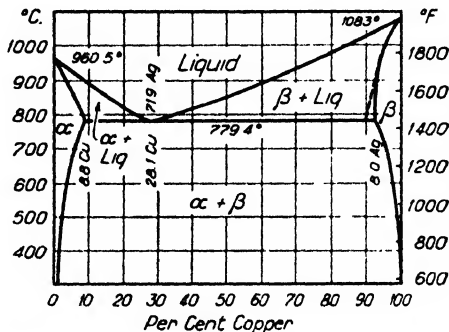


Fig. 1—The Copper-Silver Constitution Diagram.

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parameter of selected alloys quenched from a high temperature and reheated at a series of lower temperatures, and comparing the observed values with the curve of

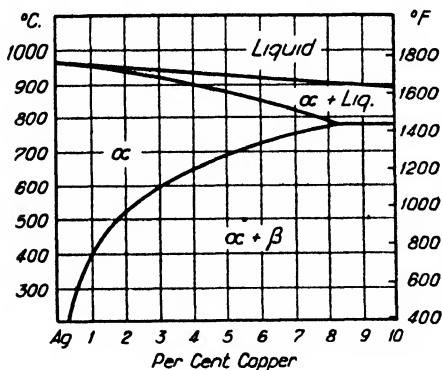


Fig. 2—The silver-rich portion of the Copper-Silver Equilibrium Diagram.

formation in an alloy containing 0.79% copper. In the complete diagram, Fig. 1, and the larger scale reproduction of the silver corner, Fig. 2, the results of Ageew and Sachs have been preferred in the low temperature ranges on account of the greater sensitivity of their method, while the curve above 500° is drawn as an average curve through both their experimental points and those of Stockdale. The solubility will be seen to be 8.8% copper at the eutectic temperature, decreasing in a smooth curve to 0.3% at 200°C. The solidus shown is that of Stockdale.

Copper-Rich Alloys—The investigations on the solid solubility at the copper end of the diagram by Stockdale²⁸ (microscopic and electrical resistance methods), Ageew, Hansen and Sachs²¹ (X-rays), Smith and Lindlie²⁹ (microscopic) and Wiest³⁰ (X-rays) gave results which differed by not more than 0.5% at any temperature. Owen and Rogers³⁰ give a solubility curve, based on lattice parameter higher solubility at 700°C. at both ends

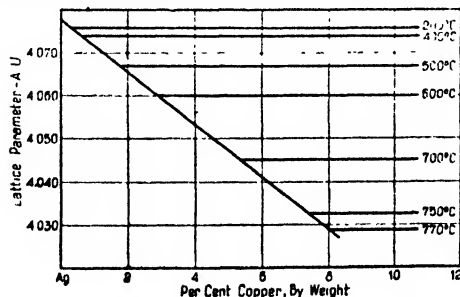


Fig. 4—The lattice parameter of the silver-rich silver-copper alloys.

that of Ageew and Sachs, outlined above, but using single-crystal wires of the alloys, found a solubility from 1.5-2% greater than in polycrystalline material, for which his results are in agreement with those of the other investigators. Doubt was thrown upon this conclusion by Schmid and Siebel,³¹ and after some controversy,³² Wiest³⁰

parameter vs. composition for a series of alloys with different copper contents quenched from 780°C., Ageew and Sachs²¹ were able to determine precisely the amount of copper in solution at each of the reannealing temperatures employed. They found the solubility to be somewhat less than Hansen showed, but their figures were practically confirmed by the work of Stockdale²⁸ who used microscopic methods at high temperatures and electrical conductivity studies below 550°C. The agreement above 500° between the investigations of Stockdale and Ageew and Sachs, which were carried out independently and by different methods, is so good that there is little doubt of the solubility at the higher temperatures, but below 500° Stockdale's figures for the solubility are somewhat higher, and he was unable to find a trans-

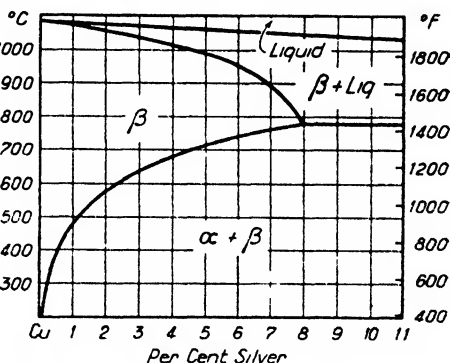


Fig. 3—The copper-rich portion of the Copper-Silver Constitution Diagram.

measurements, which shows somewhat of the diagram than other investigators show. Surprisingly, the microscopic study of Smith and Lindlie²⁹ gave the lowest solubility, although this method usually indicates a solubility rather higher than the true one. The solid-solubility curve shown in Fig. 1 and on a larger scale in Fig. 3 is drawn as an average through the experimental points of all four investigations and cannot be far from the true value. The solidus curve drawn is that of Smith and Lindlie. Stockdale's solidus curve is 50° higher at 7.5% silver and drops very rapidly to meet the eutectic line at 8.3% silver.

Wiest, using a method similar to

attributed the result to segregation, and gave new values for the parameter of single and multicrystalline material which were identical. At the same time, however, he found differences in parameter in the two-phase zone which indicated that the solubility was appreciably greater in single crystals.

Crystal structure determinations by X-ray means have been carried out by Sacklowsky,¹³ Erdal,¹⁴ Wienbaum,¹⁵ Ageew, Hansen and Sachs,¹⁶ Ageew and Sachs,¹⁷ Megaw,¹⁸ Wiest,¹⁹ and Owen and Rogers.²⁰ The results of Ageew and Sachs for the lattice parameter of the silver-rich solid solutions are shown in Fig. 4, and Ageew, Hansen, and Sachs' figures for the copper end of the diagram in Fig. 5. The face-centered cubic lattice of silver has a parameter of about 4.078 Å, a value which changes to 4.029 with 8% copper in solution. If an alloy is annealed at a temperature where it is no longer homogeneous, the excess copper will be precipitated and the parameter of the parent silver lattice will increase to a value corresponding to

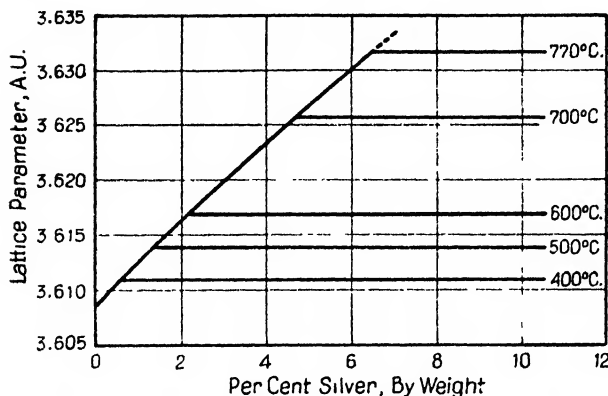


Fig. 5—The lattice parameter of the copper-rich silver-copper alloys (Ageew, Hansen, and Sachs).

that of an alloy of composition equal to the solubility limit at that temperature, regardless of the amount of copper in excess. The curve for parameter vs. copper content, therefore, consists of a horizontal straight line intersecting the sloped parameter curve at a point corresponding to the solubility at the temperature of annealing. In Fig. 4 are shown several such lines, corresponding to various temperatures.

Copper is also face-centered cubic, and has a parameter of about 3.608 ± 0.001 Å at 20°C. Additions of silver in solution up to

the solubility limit at 770°C. increase this to 3.632 Å. The X-ray diffraction pattern of alloys in the duplex range of the diagram shows lines due to both of the phases present, the parameters depending on the temperature at which the sample has been annealed and quenched, while the intensity of each set of lines will depend on the relative amount of copper and silver-rich phases present.

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Constitution of Copper-Tin Alloys

By Dr. Samuel L. Hoyt*

The copper-tin alloys were among the earliest to be studied experimentally and their historical significance gives them a special place in our list of metallic alloys. The first systematic investigations were those of Roberts-Austen, Stansfield, and Campbell for the Alloys Research Committee of the Institution of Mechanical Engineers. This work was followed immediately by the publication of the diagram of Heycock and Neville, the feature of which was the use of the principles of the phase rule, to parallel a similar treatment by Roozeboom of the early iron-carbon diagram. Shepherd and Blough, in this country, and Giolitti and Tavanti in Italy soon followed with their contributions. It is interesting to note that this early work, and particularly the now classical contribution of Heycock and Neville, gives a satisfactory understanding of this system, though certain features were left unsettled which still remain controversial today.

In 1913 the writer showed that a heat effect occurred in the alloys over the alpha plus gamma range (Fig. 1) at 590°C. which had previously been missed. Subsequent work by British, German, Japanese, and American investigators has added to our knowledge of this system, while the methods of X-ray crystal analysis have been applied to a study of the phases. The most recent findings are that on long time annealing, (a) the solubility of tin in copper decreases at lower temperatures and (b) the delta phase, of Cu_3Sn , changes to alpha plus eta, or Cu_5Sn , at about 330-350°C.

The copper-rich portion of the copper-tin diagram is reproduced in Fig. 1. This is essentially the diagram of Heycock and Neville¹ and was laid down by melting point determinations and by microscopic examination of heat treated samples for the determination of the fields within the solid state. The more important features of the constitution of this system may be listed as follows:

(1) Tin lowers the melting point rather rapidly from 1083°C. for pure copper to $795 \pm 5^\circ\text{C}$. at 25% tin. Above 25% tin the effect is less pronounced.

(2) The first additions of tin enter copper in solid solution to form the alpha or common low-tin bronzes. The amount of tin which is dissolved is not over 16%, which is the saturation concentration,² but is much less than this for ordinary cooling rates. The apparent solubility is about 5% tin for chill castings and is in the neighborhood of 10% for slowly cooled alloys. It may be increased to more than this by moderate annealing operations. The pronounced dendritic character of these alloys is responsible for these variations and gives the typical microstructure. In published diagrams there is lack of agreement for the limit of the alpha field, but the location is purely arbitrary unless the saturation value of 16% is used. In reading the diagram given here, it is to be borne in mind that the common structure of low-tin bronze is definitely dendritic and that the apparent limit of solubility is well below that given by the vertical, dotted line at 16% tin (for a discussion of this line, see below).

(3) Two peritectic reactions or equilibria occur over this range of tin at which new solid phases become stable with the melt. The solid phases are known as alpha, beta, and gamma. The alpha phase has been discussed. The beta and gamma phases are responsible for transformations in the solid state. Heycock and Neville were not able to distinguish microscopically between these two phases and this has been confirmed by Matsuda.

(4) When the tin content exceeds that which is present in the alpha solid solution, the excess forms a typical eutectoid structure of alpha and delta by the eutectoid transformation, $\text{gamma} = \text{alpha} + \text{delta}$. When the tin content is in the neighborhood of 10% or less, the delta phase can be eliminated by ordinary annealing.

(5) Over the range of composition which is covered here there is one more room temperature phase, the intermetallic compound Cu_5Sn . With additional tin in solid solution it is the phase, eta, of the diagram. This phase is polymorphic and transforms into gamma at 670°C. The delta phase has been considered to be an intermediate solid solution, rather than an intermetallic compound, mainly because its physical properties did not fit the current conceptions of compounds. More recently X-ray crystal analysis shows that this phase must be the compound,

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Cu_3Sn . The ranges of composition of the phases delta and eta are not known definitely.

(6) An interesting feature of the copper-tin alloys is the partial fusing of those containing just above 40% tin, after having once solidified completely.

The first 6 features have been well established and they are generally accepted. There are some additional features which have not been definitely settled by the work which has been done to date. Fortunately, for the practical handling of these alloys they give no difficulty from that score.

(7) A thermal critical point was discovered by the writer, in the alloys from 12-26% tin at 580°C . This point has been verified by the Bureau of Standards and by various others since then. The transformation which is responsible for this heat effect has been the subject of considerable experimentation and discussion. The writer found that the maximum heat effect was well towards the right of the alpha plus gamma field of Fig. 1. It was held that the effect was associated with the beta phase and he suggested the eutectoid change of beta as a possible explanation. However, it was not until Bauer and Vollenbrück conducted their careful

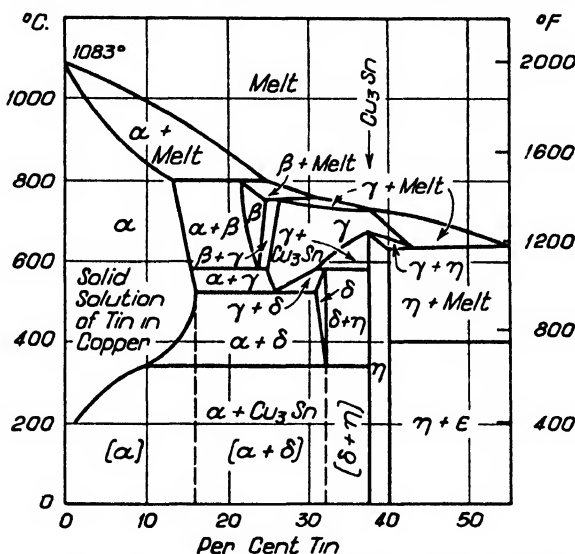


Fig. 1—Copper-rich portion of the copper-tin constitution diagram.

study of this system that the construction of Fig. 1 could be held to be adequately supported.⁴ The major objection to this construction has been the failure to observe a typical eutectoid structure but this objection is no more serious here than it is in the case of the corresponding situation with the eutectic which lies close to one of the components. Other investigators have published results which do not agree with the construction of Fig. 1 and have suggested different explanations for the heat effect at 580°C . Noteworthy among these is that of Isawa⁵ who concluded from X-ray evidence that beta undergoes a change in superstructure at this temperature. This idea appears to be supported by the microstructure of these alloys but does not agree with what one would expect from a study of the ternary alloys with zinc which show a large heat effect at this temperature and a phase change.⁶

(8) The gamma phase of composition Cu_3Sn has been assumed to solidify over a range of temperature (Heycock and Neville, Shepherd and Blough) while Giolotti and Tavanti, and Bauer and Vollenbrück⁴ record a constant freezing point for this composition. Matsuda⁷ likewise checked this point, as did the writer, and came to the same conclusion. This latter construction has been incorporated in the diagram, and is consistent with physical tests made on the molten copper-tin alloys which indicate the presence of this compound in the liquid state. Hamasumi and Nishigori also checked this point, but concluded that it was an alloy with lower tin content that had the constant freezing point.⁸

(9) The transformation at 580°C , involving delta has been variously explained, and is usually associated with a eutectoid or peritectoid change, or with both.

In the last case, a second horizontal is shown. It is not possible to represent the phase relationships in this region in a way which reconciles the conflicting opinions. The construction shown is that used in a number of recent diagrams.

The most drastic change in the equilibrium relations of the copper-tin alloys is introduced in the diagram of Fig. 1. Owen and Iball,⁹ Owen and Williams,¹⁰ and Haase and Pawlek¹¹ have shown that the alpha solid solution precipitates delta at temperatures above 330-350°C. and eta below that temperature. The alpha phase shifts its saturation concentration about as is shown by the solid line. This occurs only with prolonged annealing and the usual microstructure occurs in accordance with the statements in point (2). For this reason the dotted vertical at 16% Sn is used while the metastable structures are indicated in [].

The difficulties involved in the experimental and theoretical elucidation of the controversial features of this system are rather great, and this accounts for the lack of agreement among the published diagrams. More recent work suggests that the diagram is much more complicated than that of Fig. 1. Referring to paragraph 9 above, for example, Hamasumi and Nishigori¹² report two eutectoids and two peritectoids for that region alone and their construction was based on a careful and detailed study of the constitution of this system.

The methods of X-ray crystal analysis have been used to show the atomic arrangement of the phases of this system. The alpha solid solution is face-centered cubic while the lattice parameter increases from 3.608 Å for pure copper to 3.695 Å for 15% tin alloy.⁹ Mehl and Barrett¹³ have shown that the tin atoms occupy positions on the copper lattice, by substitution. The next phase is delta, and it has a face-centered cubic atomic arrangement with 416 atoms per unit cell and a lattice parameter of 17.92 Å. This is the same structure as that of gamma brass in which it was first discovered and X-ray metallographers use the name gamma for this phase of the copper-tin system, and for all others of the same structure. This work showed that this phase is not Cu₃Sn, but Cu₁₁Sn₃. The phase Cu₃Sn, or eta, has a hexagonal close packed arrangement with 62 atoms per unit cell, $a = 2.75$ Å, and $c/a = 1.57$. (See also reference 10.) This arrangement was first found in the epsilon phase of brass and hence this copper-tin phase, and all others of the same structure, have been given the common name of epsilon. The high temperature phase gamma has the same body-centered cubic arrangement as beta brass with a parameter of 2.972 Å so that this, and other similar phases, are called beta.¹⁴

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The Constitution of the Copper-Zinc Alloys

By Arthur Phillips* and R. M. Brick**

With the exception of a few isolated references to the solubility of zinc in copper, the literature on the copper-zinc constitution diagram offers little of significance prior to 1896 when Charpy¹ reported the results of a study of the microstructure and mechanical properties of brasses containing up to approximately 50% zinc. In 1897, Roberts-Austen² published the first complete liquidus curve together with the several peritectic horizontals. He also indicated a "eutectic" at 450°C. in alloys containing 25-45% zinc. In a second paper, Charpy³ questioned the presence of the eutectic. This subject was the basis of a controversy which has persisted to the present day.

Shepherd⁴ offered the first complete constitutional diagram which was assembled from data obtained by thermal and microscopic analysis. Subsequent investigators have made free use of this diagram. Shepherd, however, failed to find the 450°C. horizontal reported by Roberts-Austen. Guillet's⁵ results were essentially a verification of Shepherd's work. Tafel⁶ and Parravano modified Shepherd's liquidus and solidus curves. Tafel also believed Roberts-Austen to have been in error with regard to the 450°C. horizontal.

Carpenter and Edwards⁷ proved without question the presence of the transforma-

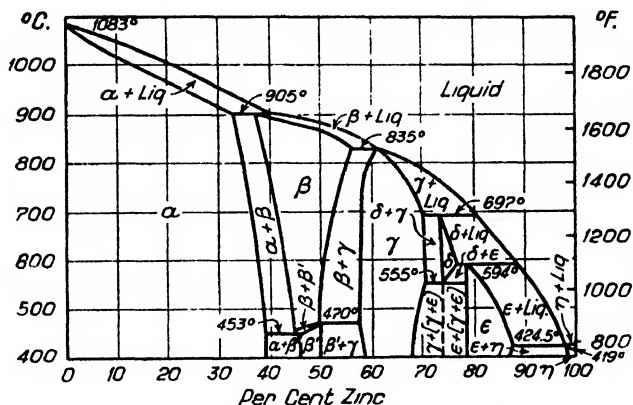


Fig. 1.—Constitution of copper-zinc alloys.

tion point found by Roberts-Austen and attributed it to a eutectoid inversion of beta into alpha plus gamma. In two later papers Carpenter,^{8,9} offered photographic evidence which seemed to prove his contention that beta brass below 470°C. consists of alpha and gamma associated in a state of division just within the resolving power of the microscope. Hudson¹⁰ rejected Carpenter's interpretation in favor of an explanation based on a polymorphic transformation of beta into a beta modification which could not be distinguished from beta by microscopic examination.

Mathewson and Davidson¹¹ determined the boundary curve between the alpha and the alpha plus beta fields; they also indicated the curve separating the beta and the alpha plus beta fields on the basis of experimental results obtained in the Hammond Metallurgical Laboratory, but not reported in their paper. Matsuda¹² published an incomplete diagram extending from 70-30% copper, assembled from microscopic and physical data. A month later, Imai¹³ presented a diagram based entirely on electrical resistance measurements. Both Matsuda and Imai suggested that the beta transformation is associated with no change of phase but consists of a change in atomic energy, analogous to Honda's interpretation of the A_2 transformation in iron. Masing,¹⁴ Helke and Ledebur,¹⁵ and Andrew and Hay¹⁶ published none too convincing evidence in favor of the eutectoid inversion of beta.

Genders and Bailey¹⁷ by microscopic examination of brasses annealed after chill casting extended the limit of the alpha phase to a lower copper content than that

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determined by Mathewson and Davidson; they placed the solubility of zinc in copper at 39% at 400°C. Their alpha limits were later confirmed by Gayler.³⁰ Haughton and Griffiths³¹ by electrical resistivity measurements determined the beta transformation temperature in brasses containing 46-62.6% copper. Their work showed conclusively that the temperature became higher as the zinc concentration of brasses containing beta increased, as had been previously suggested by Mathewson and Davidson and others.

Jitsuka³² and Bauer and Hansen³³ offered complete revisions of the copper-zinc diagram. The latter authors made a critical review of the literature and their diagram composed of accepted data, supplemented by a large amount of original work, undoubtedly represents the most authoritative work on the subject. Jitsuka suggested a double transformation of the beta constituent $B \rightleftharpoons B_1 \rightleftharpoons B_{11}$. Schramm has investigated the peritectic temperatures and concentrations. In general, his results are in agreement with the results of Bauer and Hansen.

X-ray investigation by means of lattice parameter measurements have been carried out by a number of workers^{34, 35, 36, 37} and are in fair agreement with the findings by other methods. Studies of the structure of the alpha phase have been made by Bain;³⁴ of the beta by Westgren and Phragmén,³⁵ Owen and Preston,³⁶ and Phillips and Thelin;³⁷ of the gamma by Bradley and Thewlis³⁴ from Westgren and Phragmén's data and more recently by Bradley and Gregory;³⁸ the epsilon and eta by Westgren and Phragmén³⁵ and Owen and Preston.³⁶

Table I
X-Ray Data

Phase	Structure	Lattice Constants Å
Alpha	Face-centered cubic.....	100% Cu = 3.608
Beta	Body-centered cubic, CuZn.....	62.5 Cu = 3.693
Gamma	Cubic-low symmetry, 52 atoms/cell, Cu ₅ Zn ₈	2.942
		2.949
		8.837
		8.874
Epsilon	Hexagonal close packed.....	Saturated with Zn at 200°C.
		a ₀ = 2.762
		c ₀ = 4.308
		c/a = 1.560
Eta	Hexagonal close packed.....	2.6% Cu
		Zn
		2.6732 2.6590
		4.8125 4.9351
		1.8012 1.8560

It was believed by Straumanis and Weerts³⁹ and von Steinwehr and Schulze⁴⁰ that the beta-beta prime transformation is a change in atomic distribution, probably from a random to an orderly arrangement. Moser,⁴¹ Mott⁴² and Sykes and Wilkinson⁴³ assumed the ordering to be analogous to that found in Cu₃Au, with copper atoms situated at the cube corners and zinc atoms at the cube centers. On this basis, the experimentally determined specific heat change during the beta-beta prime transformation was found to be in good agreement with the energy changes predicted by order-disorder theories, particularly the local ordering of Bethe. Recently Jones and Sykes⁴⁴ using X-rays of zinc K radiation have obtained photographs which show superlattice lines, thus producing the first direct evidence of an ordered structure in beta prime at room temperature. According to Kaminski and Kurdjumow another transformation to a face-centered tetragonal ordered structure occurs in beta brass at -14°C. The new structure, designated alpha prime, has the dimensions, a = 3.755, c = 3.586, c/a = 0.955.

In Table I are compiled the most recent and probably the best data on structure and the lattice constants at room temperature at the concentration limits of each phase. Compound forms on which the phases are based are also listed where known.

The diagram of Fig. 1 has been assembled from data carefully selected from many of the sources previously mentioned. It is difficult to make adequate and detailed acknowledgments of the many investigators contributing to this diagram. Certain specific statements may be made, however, relative to the selection of boundary lines in the parts of the diagram containing alloys of industrial importance.

The alpha and beta liquidus and solidus lines have been drawn from the

combined data of several works, particularly Parravano and Tafel. Bailey and Gender's work, confirmed as it has been by others, has been accepted in placing the alpha solubility curve. The course of the beta transformation, extending from 453-470°C. from the alpha to the gamma solubility curves has been taken from the data of Haughton and Griffiths. A double line extending through the beta field, represents a narrow B + B₁ field, as originally shown by Mathewson and Davidson and more recently by Bauer and Hansen. The zinc-rich end of the diagram has been accepted as offered by Anderson, Fuller, Wilcox, and Rodda.¹² The remainder of the work has been largely derived from the results of Jitsuka, and Bauer and Hansen. The diagram, Fig. 1, is in good agreement with that published by Hansen,¹⁴ whose recent book should be consulted for complete references to all work on Cu-Zn alloys up to 1936.

Certain important concentration and temperature limits have been assembled in Table II:

Table II
Concentration Limits and Temperatures of Peritectic Horizontals

	Copper, %	Temp., °C.
Alpha + Liquid.....	67.5-63	-61.5
Beta + Liquid.....	43.5-	-39.3
Gamma + Liquid.....	30.0-27.0-19.5	697
Delta + Liquid.....	23.5-21.5-11.5	594
Epsilon + Liquid.....	12.5- 2.7- 1.9	424.5
Eutectoid $\delta \rightleftharpoons \gamma + \epsilon$	29.5-26.0-21.5	555

Concentration Limits at 400°C.			
	Copper, %	Copper, %	
Alpha	100.0-61.0	Epsilon	21.5-13.5
Beta	54.5-50.0	Eta (424°C.)	2.66-0
Gamma	41.5-32.5	Eta (100°C.)	0.40-0

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Constitution of Copper-Nickel-Tin Alloys

By J. T. Eash*

Investigations of the constitution of alloys of copper-nickel-tin have for the most part been limited to alloys of high copper content. While considerable controversy exists over certain features of the binary copper-tin diagram, the most important being the beta and gamma transformations and the exact domain of the alpha solid solution at low temperatures, the various investigations of the ternary copper-nickel-tin alloys are qualitatively in agreement, with the possible exception of the alpha domain only at low temperatures and the nature of the secondary phase in alloys just exceeding the alpha boundary (references 1-4).

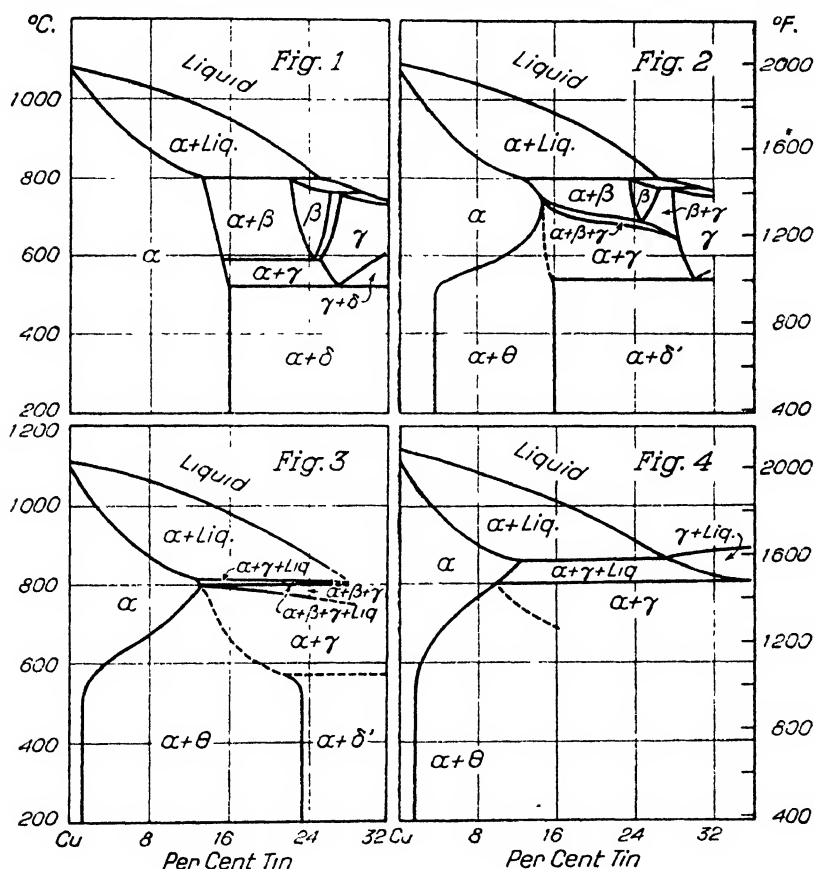


Fig. 1—The copper-tin constitution diagram. Fig. 2—Constitution diagram for nickel-copper-tin alloy with 2% nickel. Fig. 3—Constitution diagram for nickel-copper-tin alloy with 5% nickel. Fig. 4—Constitution diagram for nickel-copper-tin alloy with 10% nickel.

Due to the complexity of the relations existing in the ternary system, the constitution of the alloys of copper-nickel-tin is most readily considered from a standpoint of quasibinary sections at constant nickel levels. The equilibrium relations existing in nickel-free copper-tin alloys is represented in Fig. 1 which is a combination of the diagrams of Stockdale⁵ and Bauer and Vollenbruck⁶ and similar to the diagram presented by Hoyt on page 1364. A diagram of the equilibrium relations existing in the ternary alloys through a section at 2% nickel, as determined

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by Eash and Uphengrove,³ is shown in Fig. 2. The addition of nickel causes a marked decrease in the solubility of tin in the alpha phase and the resultant separation of a secondary phase, theta, which has been found through the use of polarized light to differ from the delta phase of the higher tin content alloys. The transition of the beta phase to alpha + gamma, which occurs at 587°C. in binary copper-tin alloys, takes place in 2% nickel alloys over a range in temperature as shown by the alpha + beta + gamma field. The beta transformation does not yield a eutectoidal structure of alpha + gamma but is merely a change to these two phases in a step-wise transition in which beta transforms to gamma which has a lower affinity for copper and allows the separation of alpha. The area of the beta field is smaller and the beta + gamma field is wider than the corresponding areas in the binary copper-tin system. The inversion of gamma to alpha + delta prime occurs at 539°C. which is 19° higher than in nickel-free alloys. The alloys of high tin content in the alpha + delta prime field have a eutectoidal structure while alloys in this field having a lower tin content (16-20%) may or may not develop a eutectoidal structure depending on the rate of cooling. A slow rate of cooling is inductive to the formation of clear delta prime while a relatively more rapid rate produces the alpha + delta prime eutectoid. The delta prime phase is distinguished from the other constituents by the structure observed under polarized light which indicates

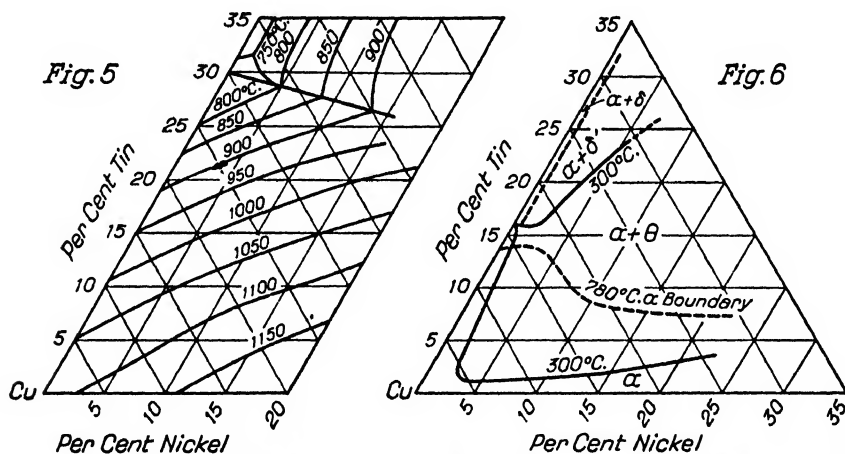


Fig. 5—Liquidus temperatures of copper-nickel-tin alloys (Veszelka, Eash, and Uphengrove). Fig. 6—The 300°C. isotherm and the alpha-phase boundary at 780°C. (Eash and Uphengrove).

that it is anisometric. The theta phase is isometric. While delta of the straight copper-tin alloys has the same appearance as delta prime under ordinary microscopic examination, the former differs in being face-centered cubic with 416 atoms to the unit cell⁷ and gives an isometric reaction under polarized light. A small amount of nickel is sufficient to change this cubic structure to perhaps a tetragonal or a hexagonal phase.

The addition of 5% nickel produces the changes shown in Fig. 3. The liquidus and solidus temperatures shown in this section are a combination of the work of Veszelka⁴ and Eash and Uphengrove³ while the solid transformations are from the work of the latter only. The alpha + beta + gamma domain is restricted to higher temperatures as the nickel is increased until at some 7% nickel the beta phase is no longer present and the alpha + gamma field then extends up to the solidus plane. The delta prime phase in the 25-30% tin, 5% nickel alloys is clear and not eutectoidal after slow cooling.

A section at 10% nickel showing the liquidus and solidus temperatures, as given by Veszelka, and the alpha phase boundary as determined by Eash and Uphengrove is given in Fig. 4. While the liquidus temperature is raised gradually with each addition of nickel as shown in Fig. 5, the peritectic horizontal of the alloys containing 14-25% tin is not raised appreciably until nickel additions exceed 10%. In

alloys containing up to 10% nickel the solidus horizontal remains at 800°C., but the addition of 15% nickel raises it to 865°C. The annealing of heterogeneous castings must therefore be carried out at temperatures below 800°C.

A ternary diagram showing the phases existing at 300°C. (572°F.), together with the alpha phase boundary at 780°C. (1436°F.) is given in Fig. 6. Due to the changes in solubility of tin in the alpha phase with variations in temperature, the alloys in the heterogeneous alpha + theta field may be age hardened. It has been demonstrated that a wide range of these alloys are subject to age hardening, the range extends at least up to 40% nickel and 11% tin.^{1,2,3,4} By the proper selection of composition and heat treatment very striking and useful properties may be secured, the increase in hardness and proportional limit coupled with good ductility being especially noteworthy.

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Constitution of Copper-Nickel-Zinc Alloys

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Until recent years our knowledge of the constitution of these alloys was limited to alloys containing up to about 20% nickel and 70% zinc, (with the exception of the work of Tafel in 1908 who reported the liquidus for the entire system) and was due to the work of several investigators^{1, 2, 3}, especially Bauer and Hansen.⁴ In 1935 J. Schramm¹⁴ published a comprehensive treatise presenting the results of thermal, microscopic and X-ray investigations of the entire system. The diagrams presented in this article are those of Schramm re-orientated so that the base line

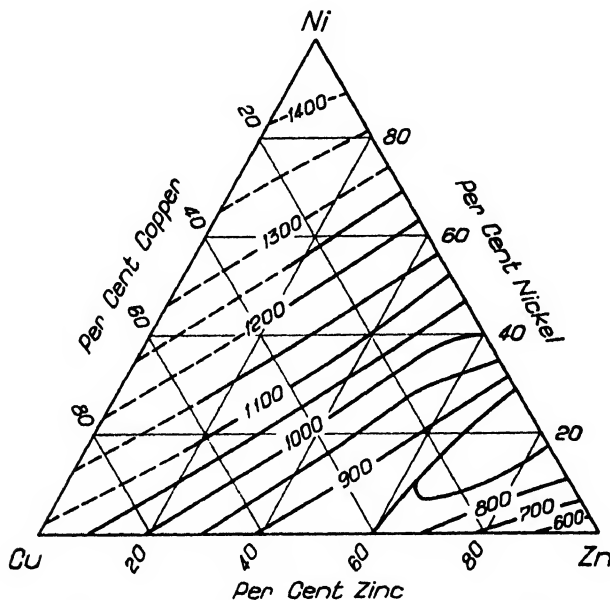


Fig. 1—Liquidus temperatures in °C. copper-nickel-zinc system (Schramm¹⁴).

will represent the binary copper zinc alloys, since the commercially important nickel silvers are essentially brasses containing up to 25% of nickel.

The liquidus surface of the copper-nickel-zinc system is shown in Fig. 1 and the constitution of the alloys at 775°C., 650°C., 25°C. in Fig. 2, 3, 4. With the exception of the alpha phase boundary at 400°C. (and 25°C.), Schramm¹⁴ and Bauer and Hansen⁴ are in good agreement on the location of the boundaries of the alpha, alpha + beta, beta, and beta + gamma fields for temperatures up to 800°C. and alloys containing up to 20% nickel, beyond which nickel content Bauer and Hansen present no data.

From Fig. 2, 3, 4, it may be seen that the face-centered cubic alpha phases of the binary systems Cu-Zn and Ni-Zn form a continuous solid solution, the alpha domain narrowing somewhat with decreasing temperature.

The beta phase of the copper zinc system, stable below 470°C., is body-centered cubic β_1 and that of the nickel-zinc system, stable below 875-800°C., is of the Au-Cu type of tetragonal lattice and designated β_2 . Schramm therefore indicates a two phase field in the ternary system in which β_1 and β_2 are co-present. The area of the two-phase field is sharply restricted at 775°C., and broadens moderately, and shifts to higher copper contents with decreasing temperature. According to Schramm, nickel raises the temperature of the β to β_1 transformation of the Cu-Zn binary system until it coincides with the solidus and disappears. Schramm does not indicate the transformation in the sections at 650 and 775°C. (Fig. 2 and 3),

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but simply shows the β' phase to be shifted to higher nickel concentrations as the temperature is raised.

The gamma phase is common to the entire system, the gamma phases of the binary systems forming a continuous solid solution. The structure is indicated as a cubic of low symmetry (52 atoms per cell). Bauer and Hansen,⁸ Yamaguchi,¹² and Schramm¹⁴ are all agreed on the isomorphism of the gamma phases of the Cu-Zn and Ni-Zn systems.

A three-phase region exists on either side of the $\beta' + \beta_1$ two phase field, between room temperature and some temperature slightly in excess of 650°C., the one field containing α , β' and β_1 , and the other γ , β' and β_1 , both of these fields apparently increasing in area and shifting to lower nickel contents with decreasing temperature. At 775°C., the $\gamma + \beta' + \beta_1$ field is not indicated since the β_1 field exists over a very small area and does not meet the $\beta' + \gamma$ phase field boundary. According to Schramm's interpretation, some of the 13-15% nickel extrusion alloys might be expected to contain α , β' and β_1 at room temperature under equilibrium conditions, although if such is the case no mention has been made of it in the literature. At 400°C. the $\alpha + \beta' + \beta_1$ field has been shifted to beyond the range of composition of the commercial nickel silvers.

The phase relationships in the zinc corner of the diagram at room temperature are rather complicated, as may be observed from Fig. 4. The phase of the nickel zinc system designated by Schramm as delta, and possessing an hexagonal lattice, is reported to form an unbroken solid solution with the delta phase of the copper-zinc system (stable above 555°C.). At room temperature (Fig. 4) the delta field of the ternary system is extremely narrow and extends to about 10% of copper. The close packed hexagonal epsilon phase of the copper-zinc system takes up very small amounts of

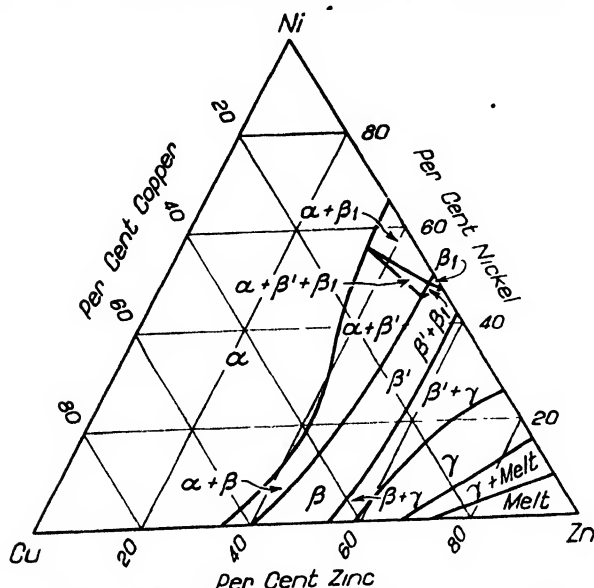


Fig. 2—Constitution of copper-nickel-zinc alloys at 775°C. (Schramm¹⁴).

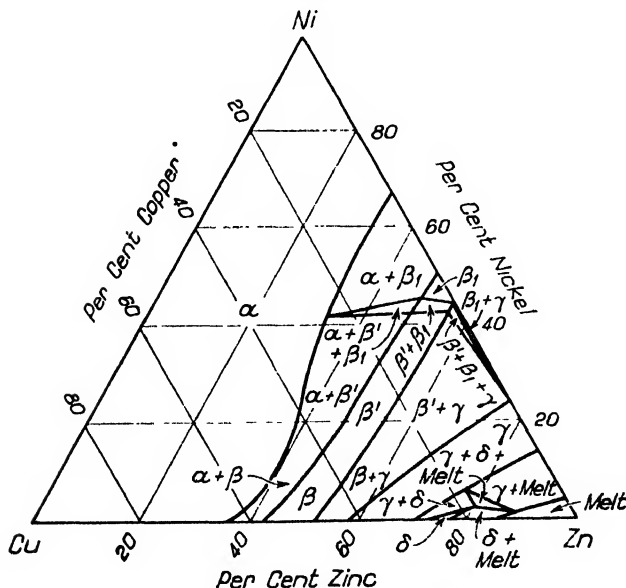


Fig. 3—Constitution of copper-nickel-zinc alloys at 650°C. (Schramm¹⁴).

(stable above 555°C.). At room temperature (Fig. 4) the delta field of the ternary system is extremely narrow and extends to about 10% of copper. The close packed hexagonal epsilon phase of the copper-zinc system takes up very small amounts of

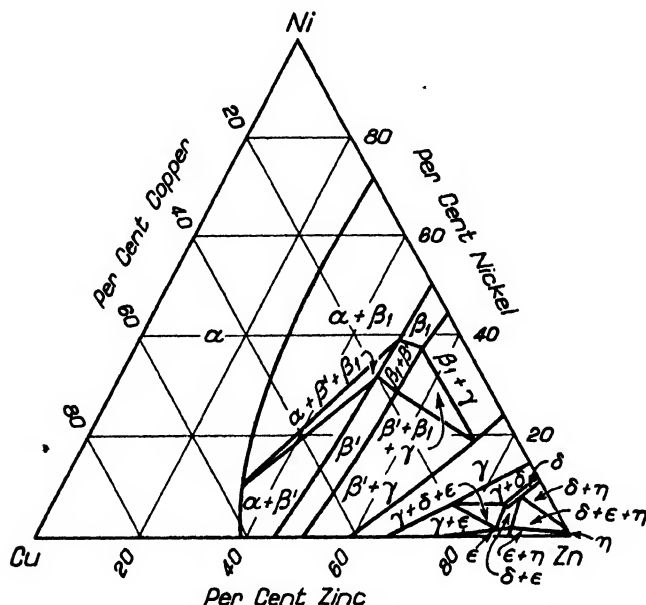


Fig. 4—Constitution of copper-nickel-zinc alloys at 25°C. (Schramm¹⁴).

nickel into solid solution. Since the solubility of nickel in zinc is of the order of 0.04%, and of copper in zinc about 0.3% (at 100°C.), the eta phase domain of the copper-nickel-zinc system is exceedingly small. The lattice of the eta phase is of the close packed hexagonal type.

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The Ternary System Copper-Zinc-Tin

By H. C. Jennison* and Cyril Stanley Smith†

In spite of the fact that it is one of the most important ternary nonferrous systems, the constitution of much of the copper-zinc-tin system remains uncertain. No data have been found for alloys with more than 30% tin, or more than 50% zinc. The work of Hansen^{1,2} and his collaborators has, however, elucidated the structure of the copper-rich alloys satisfactorily and this article is largely based on their work.

The constitution of any ternary system is, of course, related to the binary systems composing it, and it will be appreciated that the uncertainty in the copper-tin system (see article on page 1364 of this handbook) is present to an even greater extent in the ternary systems based upon it. The copper-zinc system is better established (page 1367 of this volume). The zinc-tin system has a eutectic at 9.0% zinc and 199°C. (page 1756 of this handbook). This eutectic is formed between zinc and tin, each with a very small amount of the other metal in solid solution. No other phases are present.

The liquidus surface (melting point) of the ternary system was first determined by Hoyt^{3,4} in 1913, who also described the microstructure of the alloys and outlined the alpha, beta and gamma fields. Prior to this Guillet⁵ had studied the structure of cast alloys in an attempt to determine a coefficient of equivalence for the substitution of tin in the brasses.

The work of Hudson and Jones⁶ established the alpha, beta, and gamma fields near the copper-zinc side of the diagram of 425°C. Campbell⁷ determined the limits of the microstructural fields in the copper-rich alloys in the cast condition and after annealing at 650°C.

X-ray studies of the parameter and limit of existence of the alpha phase in the ternary system have been made by Konobejewski, Tarassowa and Stepanova.⁸

Tammann and Hansen¹ in 1924 reported the results of thermal studies and a limited amount of microscopic work on the basis of which they drew a diagram above 50% copper, omitting the area beyond the appearance of the gamma phase. This work forms the basis of Fig. 1, which shows the liquidus isothermals of the system. Tammann's and Hansen's lines have been displaced somewhat in the region from 50-70% copper and up to 10% tin, in which preference for the more detailed work of Bauer and Hansen⁹ has been given. This latter paper, which includes a critical review of all earlier work on the system, contains an accurate experimental study of the limited region from 50-70% copper and 0-6% tin.

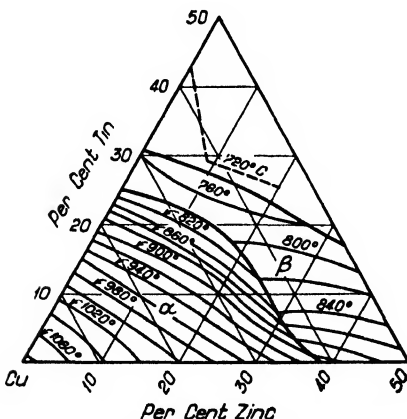


Fig. 1—Liquidus isothermals of the copper-zinc-tin system.

Liquidus Surface—The melting point of copper is decreased by addition of either zinc or tin, or both. The sloping liquidus lines in the binary systems become a sloping surface in the ternary model. The isothermal lines of Fig. 1 represent the contours of this surface. The heavy line running from 61.5% copper and no tin to 25% tin with no zinc is the intersection of the peritectic surface with the liquidus; to the copper-rich side of this the alpha phase is the first to solidify from the melt, and on the other side, the beta phase. The second heavy line represents the other limit of the primary beta field, and is followed by gamma or uncertain phases related to those in the copper-tin system.

The solidus has not been well established. According to Tammann and Hansen, the peritectic horizontal of the copper-tin system continues as an almost horizontal surface across the ternary model at a temperature of about 800°C., but rapidly inclines and rises to join the copper-zinc peritectic at 905°C. in that range below about 10% tin. Practically, this means that a vertical section passing through the

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copper corner of the ternary diagram and thus representing a constant ratio of tin and zinc is almost identical with the copper-tin system with a distorted composition scale until the zinc exceeds over four times the tin content. The same applies to the solid phases and a eutectoid similar to that in the copper-tin system exists in alloy containing as little as 4% tin with 38% zinc. Of course, all horizontal lines in the binary systems become double, usually curved, and not necessarily horizontal in the ternary system, but the displacement in this part of the present system is very small.

Both the alpha and the beta phases in the two binary systems are isomorphous—that is, they have the same crystal structure and form an unbroken series of solid solutions with each other, in which zinc can be replaced by tin and vice versa without introducing new phases. In the copper-zinc system the beta phase is stable (except for a change to a disordered structure) at all temperatures up to the melting point, but the corresponding phase in the copper-tin system is unstable at temperatures below 520°C. and it is therefore impossible for the ternary beta phase to extend right across the diagram below this temperature. Actually the ternary beta phase continues to suffer eutectoidal decomposition at almost the same temperature as in the binary copper-tin system until within about 3% of the copper-zinc binary side, when the beta boundary rapidly falls to lower temperatures, forming stable beta.

The eutectoid line at 520°C. in the binary copper-tin diagram, on which beta is in equilibrium with both alpha and gamma, becomes, as it extends across the diagram, a narrow band in which all three phases can co-exist over a small temperature range. This spreads to cover a wide range of temperature underneath the beta phase just before the beta boundary descends near the zinc side of the diagram.

These facts are represented in Fig. 2 which is a horizontal section of the diagram at 500°C. This shows the maximum extension of the alpha phase, and is just below the temperature at which most of the ternary beta phase has undergone eutectoidal transformation to alpha plus gamma. A similar section at a temperature above 520°C. would show the beta phase extending right across the diagram in a band of width increasing with temperature up to the solidus, and the three phase zone of alpha plus beta plus gamma would disappear.

The alpha phase boundary in Fig. 2 is that shown by Konobejewski and his co-workers. This is based on lattice parameter determinations, assuming a plane Vegard surface, and, even though rather few alloys were used, is probably quite accurate. Konobejewski and Tarassowa¹ had previously shown that the alpha boundary in the copper-tin system fell to very low solubilities at low temperatures, and the same behavior was found in the ternary system. Konobejewski and Tarassowa¹ even found a slight decrease in solubility (down to 33.3% zinc at 167°C.) in the much studied copper-zinc series. The dotted line in Fig. 2 shows their results for the ternary system at 300°C. It should be pointed out, however, that although this line represents equilibrium conditions, reactions at these temperatures are so very sluggish that for all practical purposes the solubility should be considered as that shown at 500°C.—unless indeed the good elastic properties of the tin bronzes at room temperatures are due to their inherent instability.

The delineation of the gamma field is difficult. Although gamma copper-zinc and delta copper-tin, both with an electron-atom ratio of 1.62, have the same type of cubic crystal structure and therefore could be isomorphous, they do not seem to form an unbroken series of solid solutions with each other. Beyond this little can be said. Delta copper-tin is unstable below 380°C. and the stable phases over part of the ternary diagram at low temperatures, must, therefore, be alpha plus epsilon copper-tin or a phase derived from it by substitution of zinc for some tin

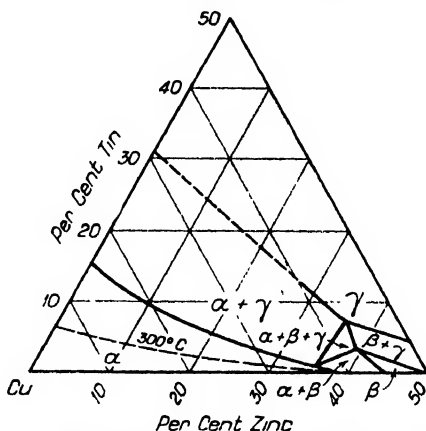


Fig. 2—Horizontal section of the copper-zinc-tin constitution diagram at 500°C.

atoms. In the zone rich in tin in Fig. 2 the phase labeled gamma may be gamma, delta, both, or perhaps neither.

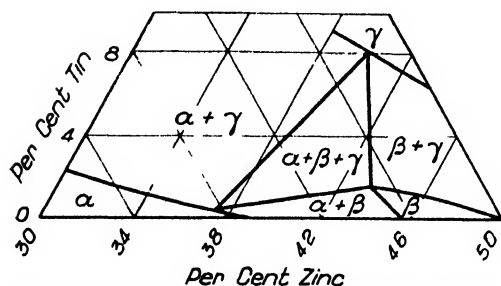


Fig. 3—Portion of diagram of copper-zinc-tin alloys of most importance.

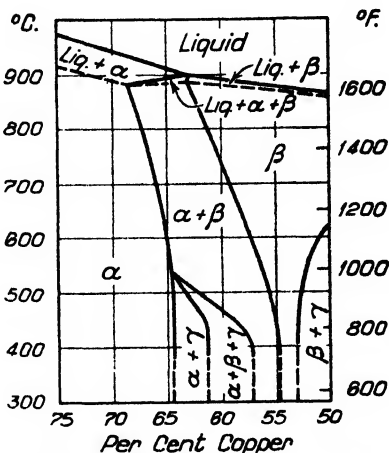


Fig. 4—Vertical section of copper-zinc-tin alloys containing 1% tin.

Because of the industrial importance of alloys of the alpha beta brass type containing small additions of tin, that part of the diagram relating to these is reproduced in a larger scale in Fig. 3 taken directly from the work of Bauer and Hansen,² and representing their results at 400°C., the lowest temperature at which changes can occur rapidly enough to be of practical importance. It is interesting to note that the solubility of tin in zinc saturated alpha at this temperature is only 0.4% but beta contains 1.5% tin at saturation. Fig. 4, also from Bauer and Hansen, is a vertical section of the ternary model on a plane containing one per cent tin, parallel to the copper-zinc face.

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The Physical Constants of Copper

By Cyril Stanley Smith*

Atomic weight	63.57
Atomic volume	7.11
Crystal structure, 20°C.	Face-centered-cubic, $A_0 = 3.6078 \text{ \AA}$
Density, 20°C.	8.94 g. per cc.
Density, 1083°C. (solid)	8.32 g. per cc.
Density, 1083°C. (liquid)	7.93 g. per cc.
Melting point	1083.0°C. (1981.4°F.)
Boiling point	2325°C. (4217°F.)
Specific heat, 25°C.	0.0918 cal. per g. per °C.
Latent heat of fusion	50.6 cal. per g.
Linear coefficient of expansion, 20°C.	16.42×10^{-6} per °C.
Electrical resistivity, 20°C.	1.682 microhms (cm.)
Electrical conductivity, 20°C.	0.594 megmho (cm.)
Thermal conductivity, 20°C.	0.923 cal./cm. ² /cm./sec./°C.
Magnetic susceptibility	-0.085×10^{-6}
Electrochemical equivalent, Cu ⁺	0.32940 mg. per coulomb
Cu ²⁺	0.65880 mg. per coulomb
Viscosity, 1145°C.	0.0341 cgs. units
Surface tension, 1150°C.	1104 dynes per cm.
Reflectivity, $\lambda = 6500 \text{ \AA}$.	80%
$\lambda = 4500 \text{ \AA}$.	37%

The atomic weight figure is from the 1939 table of International Atomic Weights, as published by the American Chemical Society. The figures for the remaining properties have been selected from various sources and need a little discussion to indicate their probable accuracy. Where no references are given the values were obtained in the laboratories of the American Brass Co.

Melting Point—The melting point of copper is used as a secondary standard of temperature, the accepted value being 1083°C. Roeser^a showed that on the 1927 International temperature scale the melting point of copper as determined by thermoelectric measurements is $20^\circ \pm 0.1^\circ\text{C}$. above that of gold, the primary standard at 1063°C. Any change in the value assigned to gold on the thermodynamic scale will apply equally to copper.

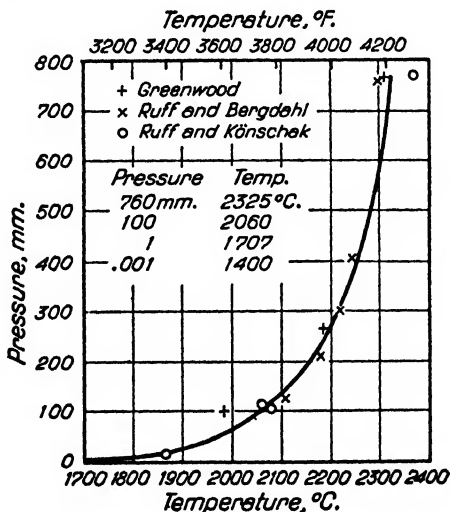


Fig. 1—Vapor pressure of copper.

+ = Greenwood²; x = Ruff and Bergdahl³; o = Ruff and Könschek⁴.

Crystal Structure—Copper is face-centered cubic in structure. By measurements of reflections from planes of high indices and by the use of 11 different characteristic

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wave lengths (assuming the I.C.T. values for these) Owen and Iball⁴ obtained the value 3.6076 ± 0.0003 Å at 16.5°C . Corrected to 20°C , this becomes 3.6078 Å, in exact agreement with the value independently obtained by the precision method of Kaiser and Barrett,⁴ 3.6078 ± 0.0001 Å. Owen and Yates, as a result of further careful study, give the value at 18°C . as 3.6077 ± 0.0002 Å. This becomes 3.6078, when corrected to 20°C . Wever and Lohrmann⁴ studied the corrections to be applied to the Debye method and gave a most probable value of 3.608 ± 0.001 Å. Ageew, Hansen and Sachs⁴ and Wiest⁴ used planes giving a high angle of diffraction, and obtained values of 3.6081 and 3.6085 ± 0.002 Å respectively. The agreement between all the recent values is remarkably good.

Density—The standard value adopted by the International Electrotechnical Commission in 1913 was 8.89 g. per cc. at 20°C ., which is the value used in all conversions of mass to volume conductivity. This figure is approximately correct for commercial copper, but is too low for copper containing no oxygen. Many years ago this laboratory found that the density at 20°C . of commercial annealed copper in which the principal impurity was oxygen existing in the form of Cu_2O could be expressed approximately by the relation

$$d = 8.933 - 0.44 (100 - \% \text{ Cu}) \text{ g. per cc.}$$

The density of pure copper is certainly as high as 8.94, which is the value required by the crystal structure. Maier⁴ gives a figure for the density of a single crystal as 8.953, and supposedly reliable figures as high as 9.0 g. per cc. have been reported for certain types of deoxidized copper solidified under unusual conditions. Lacking further evidence the figure 8.94 will be accepted as representative of the density of annealed pure copper. Cold working will decrease this value by a maximum of 0.1%. Castings of ordinary deoxidized copper will have a density of 8.8 to somewhat over 8.9. Tough-pitch copper will be much lower than this, but rarely below 8.4.

Bornemann and Sauerwald⁷ give the density of solid copper at the melting point as 8.32 g. per cc. The density of liquid copper at the melting point is 7.93 g. per cc., according to Widawski and Sauerwald⁸ who studied the density by a displacement method. Above the melting point the density increases linearly with temperature until at 1600°C . it is 7.53 g. per cc.

Boiling Point, Vapor Pressure—The vapor pressure of copper at high temperatures has been studied by several observers^{2, 3, 4, 9} whose results are summarized in Fig. 1. The average value for the boiling point at 760 mm. pressure is 2325°C . At lower temperatures the results of the various observers differ considerably and the curve can be regarded as only an approximation. Other data not shown in Fig. 1 are those of Ruff and Mugdan⁴ which agree with those of Ruff's other collaborators, and Bauer and Brummer⁴ whose results, in the range 1500 – 1850°C ., lie somewhat higher than those in Fig. 1. Hardeck⁴ and Marshall, Dornste and Norton⁴ among others have determined the vapor pressure from measurements of the rate of evaporation at temperatures below 1300°C ., where the pressure is of the order of 10^{-4} cm.

Specific Heat—In spite of the large number of investigators who have determined the specific heat of copper it is by no means easy to select a precise figure. At temperatures below atmospheric the results of Nernst,¹⁰ Eucken & Werth,⁴ Dockerty,¹¹ Kok and Keesom, Keesom and Onnes, all agree almost exactly in the range where they overlap and the curve shown in Fig. 2 is drawn through their results which are indistinguishable at the scale of plotting.

Agreement above room temperature is as poor as agreement of the low temperature results is good. No single investigation seems to be reliable for the range between 0 and 1083°C . The most probable curve, drawn in Fig. 3, passes closely through results of Bronson, Chisholm and Dockerty,¹² Seekamp¹³ and Schubel,¹³ up to about 300°C . and above this point follows Jaeger, Rosenbohm and Bottema, whose results above 600°C . are closely checked by Esser, Averdick and Grass.¹⁴ The specific heat of copper in the liquid state is given by Esser, Averdick and Grass as 0.11 cal. per g. per $^\circ\text{C}$. Umino reports 0.12 while Wüst,

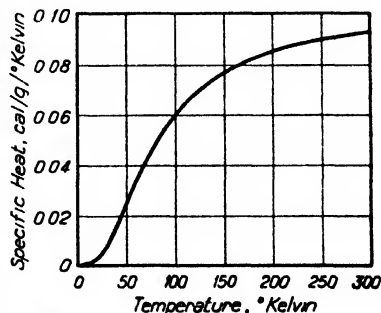


Fig. 2—Specific heat of copper at low temperatures.

Meuthen and Durrer consider the specific heat to vary from 1.0-1.3 cal. per g. per °C. between 1110 and 1300°C. Esser's figure, the most recent, has been used in constructing Fig. 2 and 3.

The precise measurements of Griffiths and Griffiths¹ and Harper⁴ in the neighborhood of room temperature agree with the curve shown in Fig. 3. The average value of Bronson and his collaborators,¹¹ Dockerty,¹² Griffiths and Griffiths,¹ and Harper⁴ at 25°C. is 0.0918 cal. per g. per °C. which is adopted for the table of data.

Latent Heat and Heat Content—Wüst and his collaborators¹ give 40.97 cal. per g. as the latent heat of fusion of copper. This is evidently a typographical error for their tabulated experimental data show a difference of 50.97 cal. per g. between the heat contents in the solid and liquid states at the melting point. This revised figure agrees with that of Umino (49.94) and Esser, Averdick and Grass (50.9). The average of these three values, 50.6 cal. per g., is probably very near the true one.

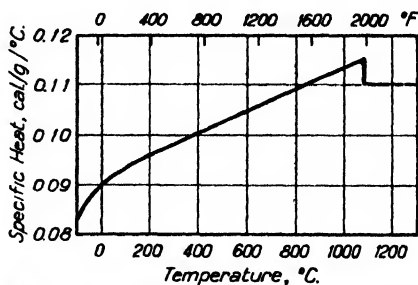


Fig. 3—Specific heat of copper at high temperatures.

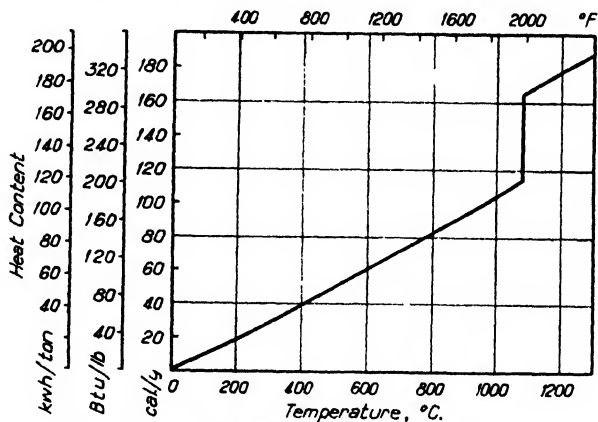


Fig. 4—Heat content of copper.

The heat content curve, Fig. 4, is not taken directly from any experimental work but is calculated on the basis of Fig. 3 and the above latent heat. The curve is believed to be more accurate than any single published work, for those who have studied the high temperature heat content have usually extrapolated to room temperatures with too high results for the specific heat. Although Umino⁹ and Wüst, Meuthen & Durrer⁸ are frequently quoted, their results are not in close agreement either with each other or with other data. Esser's curve agrees closely with Fig. 3 although the derived specific heat values at low temperatures are too high.

Linear Coefficient of Expansion—The linear coefficient of expansion of a hot rolled rod containing 99.968% copper has been determined by Hidnert,¹¹ who gave the following equation to represent his results between 16 and 300°C.:

$$L_t = L_0 (1 + 0.00001623t + 0.00000000483t^2).$$

This corresponds to a value of the instantaneous expansion coefficient at 20°C. of 0.00001642, which value is adopted as the most probable.

Uffelmann's¹⁰ results are not greatly different from these, Eucken and Dannohl¹⁰ determined the coefficient up to 825°C. and gave an equation from which the values in the following table were calculated.

Wilson and Davey¹³ give the total expansion between 27 and 1083°C. as 0.0260 cm. per cm., corresponding to an average coefficient of 24.62×10^{-6} . The total expansion from absolute zero to the melting point was found by Haring and Davey¹⁴ to be 3.01% of the length at 0°K.

Linear Coefficient of Expansion of Copper^a

Temp., °C.	Linear Coefficient of Expansion × 10 ⁻⁶ , per °C.	
	Average (0°C.-T)	Instantaneous
0	15.89	15.89
20	15.97	16.07
25	16.00	16.12
50	16.12	16.37
100	16.37	16.90
200	16.93	18.16
300	17.58	19.64
400	18.30	21.35
500	19.10	23.29
600	19.98	25.48
700	20.94	27.89
800	21.96	30.54

Cold working may increase the coefficient of thermal expansion by as much as 2%.²²

The coefficient at low temperatures has been studied by Dorsey,¹³ Keesom,²³ and Buffington and Latimer.¹⁴ A smooth curve drawn through their results gives the following approximate average values of the instantaneous temperature coefficient:

°C.	Temp. °K.	Instantaneous Coefficient of Expansion × 10 ⁻⁶	°C.	Temp. °K.	Instantaneous Coefficient of Expansion × 10 ⁻⁶
-223	50	4.4	-123	150	13.4
-198	75	7.7	-73	200	15.0
-173	100	10.1	-23	250	16.0

Electrical Resistivity—The International Annealed Copper Standard, adopted in 1913 to represent the average of high grade commercial conductivity copper, has a resistance of 0.15328 ohm (m. g.) at 20°C. This is equivalent to a resistivity of 1.7241 microhm (cm.), and a conductivity of 0.5800 megmho (cm.).

Occasional values for the mass conductivity as high as 102.8% International Annealed Copper Standard have been reported. However, the highest value obtained by The American Brass Co. on a large number of samples of annealed commercial copper since 1921 is 101.90%. Absolutely pure copper would probably have a conductivity about 1% higher, but this value has been accepted in the present tables since it represents the highest authentic determination. Using 8.94 g. per cc. as the density, this is equivalent to a volume conductivity of 0.5943 megmho (cm.), or resistivity of 1.682 microhm (cm.). If the standard value of 8.89 is used for the density the conductivity is 0.5910 megmho (cm.), but for the reasons stated above pure copper undoubtedly has a density higher than this.

The International Standard value for the constant mass temperature coefficient of resistivity is 0.00393 per °C. at 20°C. Burgess¹⁶ made an accurate determination of the coefficient between 0 and 150°C. and gave the following equation:

$$R_t = R_0 (1 + 0.0041151t - 0.0000019988t^2).$$

The resistivity of copper at high temperatures has been determined by both Northrup¹⁷ and Tsutsumi,¹⁸ whose results agree well. Northrup's results are reproduced in Fig. 5.

The electrical resistance of single crystals of copper seems to be little different from polycrystalline material of equal purity.^(21, 20, 21)

Thermal Conductivity—Lees¹⁹ gives the thermal conductivity of copper at 25°C. as 0.915 cal. per sq. cm. per cm. per sec. per °C. Schofield²⁰ determined the conductivity of a sample of copper with 99.6% electrical conductivity. Interpolation of his results gives the values in the table on the next page.

Smith,²¹ working with very pure copper of 101.66% electrical conductivity, obtained the value of 0.941 ± 0.005 cal. per sq. cm. per cm. per sec. per °C. at 20°C., the temperature coefficient being -0.000041 . This value for the temperature coefficient is probably too low. A carefully weighted mean of all the results published since 1900 is 0.9225 cal. per sq. cm. per sec. per °C., and the corresponding average

electrical conductivity is 99.6% International Annealed Copper Standard. This is the value given in the present table, although very pure copper would certainly have a conductivity about 2% higher than this.

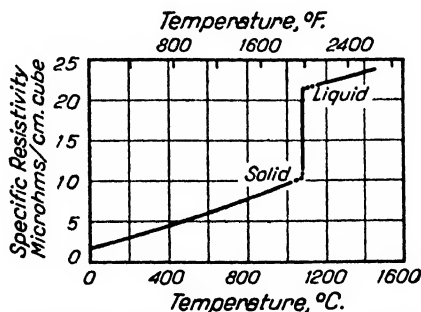


Fig. 5—Effect of temperature on electrical resistivity of copper (Northrup).

Temp., °C.	Thermal Conductivity		Temp., °C.	Thermal Conductivity	
	cal/cm ² /cm/sec/°C.	Watts/cm ² /cm/°C.		cal/cm ² /cm/sec/°C.	Watts/cm ² /cm/°C.
0	0.912	3.82	300	0.879	3.68
20	0.910	3.81	400	0.867	3.63
100	0.901	3.77	500	0.856	3.58
200	0.890	3.72	600	0.845	3.45

Angell²¹ gives the conductivity at 1000°C. as 0.80 cal. per sq. cm. per cm. per sec. per °C. Grüneisen and Goens²² give the conductivity at -190 and -250°C. as 1.33 and 21 cal. per sq. cm. per cm. per sec. per °C. respectively.

The thermal conductivity of single crystals of copper is somewhat higher than polycrystalline material, although the electrical conductivity is approximately the same. Kannaluik and Laby²³ obtained the value 0.989 cal. per cm.² per sec. per °C. at 19.4°C. for a single crystal grown by the Bridgman method.

The ratio between thermal conductivity and the product of electrical conductivity and the absolute temperature is approximately constant.

Magnetic Properties—Honda²⁴ and Owen²⁵ have determined the susceptibility of copper containing 0.008 and 0.0004% iron, the values being -0.086×10^{-6} , and -0.085×10^{-6} respectively. Endo²⁶ gives the susceptibility of solid copper at 1080°C. as -0.077×10^{-6} and liquid copper at 1090° as -0.054×10^{-6} . The susceptibility of a sample of copper measured by Haas and VanAlpen increased from -0.086×10^{-6} at 6°C. to -0.097×10^{-6} at 14 to 20°K. (-259° to -253°C.).

Watase²⁷ found the diamagnetic susceptibility of copper to be increased by elastic stress. The susceptibility also increases with decreasing particle size, the effect becoming very marked below an average diameter of 1 μ , according to the work of Rao.²⁸

Bitter²⁹ found the susceptibility of an impure paramagnetic sample of copper to increase when stretched, although annealing restored the original value. Honda and Shimizu³⁰ found a change from the diamagnetic to the paramagnetic state (susceptibility -0.083×10^{-6} to $+0.06 \times 10^{-6}$) when the samples were compressed, and a return to the original value on annealing at 250°C. or above. Banta³¹ failed to confirm this change, but later work of Lowance and Constant³² and Kussmann and Seemann³³ proved without doubt that the change was real. Kussmann and Seemann suggested that it was due to the precipitation of iron due to cold work, for the solubility of iron in copper at room temperatures³⁴ is of the order of 6×10^{-11} . They found the susceptibility after cold working to be dependent on the iron content even in the small amounts present in commercially pure copper (about 0.0001%). The susceptibility of annealed material is independent of field strength but after cold work it decreases as the field strength is increased. Shimizu³⁵ showed that copper actually becomes more diamagnetic on cold working if the values of the susceptibility are extrapolated to infinite field strength to eliminate the effect of ferromagnetic impurities. There is little doubt that Kussmann and Seemann's pre-

precipitation theory is correct, but it is probable that the effect will be partly dependent on the prior treatment of the copper.

Single crystals of copper are magnetically isotropic (Montgomery²⁰).

Electrochemical Equivalent—Taking 63.57 and 107.880 as the atomic weights of copper and silver respectively, and 1.118 mg. per coulomb as the equivalent of silver, the electrochemical equivalent is 0.3294 mg. per coulomb for bivalent (cupric) copper and 0.6588 mg. per coulomb for monovalent (cuprous) copper.

Viscosity—Bienias and Sauerwald²¹ determined the viscosity coefficient of molten copper by observing the rate of flow through a capillary tube. At 1145°C. the coefficient is 0.0341, and at 1189°C., 0.0329 cgs. units. The results do not vary uniformly with temperature and are probably accurate only to within ± 0.002 units.

Surface Tension—Smith,²² Libman,²³ and Drath and Sauerwald²⁴ give values for the capillary constant (mm²) at 1150°C. of 28.8, 30.8 and 28.81 respectively. Using Widawski and Sauerwald's value for the density (7.89 at 1150°C.), these values correspond to a surface tension of 1113, 1190, and 1113 dynes per cm. Krause and Sauerwald²⁵ give the following values:

Temp., °C.	Surface Tension Dynes per cm.	Capillary Constant (mm ²)	Temp., °C.	Surface Tension Dynes per cm.	Capillary Constant (mm ²)
1140	1120	28.35	1280	1193	30.83
1150	(1127)	(28.58)	1500	1226	32.01
1200	1160	29.70	1335	1251	32.84

The temperature coefficient of the surface tension is given as +0.66 which is remarkable both for its high value and because it is positive. Libman does not confirm this. Krause and Sauerwald seem to have used a very high density (8.04 at 1150°C.) in converting their experimental capillary constant values to surface tension, and if Widawski and Sauerwald's value is used, the surface tension becomes 1104 dynes per cm. at 1150°C., which is probably not far from the correct value.

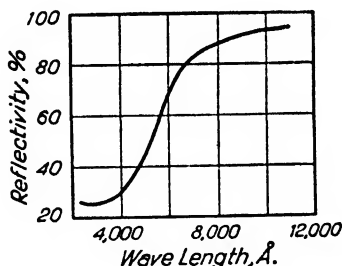


Fig. 6—Reflectivity of polished copper (Hagen and Rubens).

Optical Properties—The optical properties of polished copper have been studied by Hagen and Rubens,²⁶ Tool²⁷ and Tate.²⁸ Some of Hagen and Rubens' values for the reflectivity are reproduced in Fig. 6. The sharp increase in reflectivity at 5700 Å., responsible for the red color of the metal, will be noticed.

The relative emissivity of solid and liquid copper was determined by Stubbs²⁹ who obtained the following results:

Wave Length, Å	Solid, 1000 °C.	Emissivity % Liquid, 1125 °C.	Wave Length, Å	Solid, 1000 °C.	Emissivity % Liquid, 1125 °C.
7000	8.7	11.8	5500	31.3	29.3
6500	11.2	14.8	5000	40.4	38.7
6000	18.5	20.5			

These results agree well with those of Burgess,³⁴ and with the values calculated from the reflectivity figures.

Mechanical Properties—Although commercial copper regularly contains over 99.9% copper, it is very difficult to give definite values for the tensile properties of absolutely pure copper, since even minute amounts of impurities have considerable effect. Hanson, Marryat and Ford²² give the following figures for rolled and annealed copper rod, % in. dia., containing 0.015% oxygen and about 0.005% iron as the sole detectable impurities.

Tensile strength.....	31,790 psi.
Elongation ($L = 4\sqrt{A}$).....	58.0%
Reduction of area.....	72.8%

The tensile strength of copper varies considerably not only with the composition but also with the mechanical and thermal treatment to which it has been subjected. This is described in more detail in the article on Commercial Copper in this Handbook.

Large crystals of copper may be grown by a process of critical straining and annealing, or even by hot rolling under suitable conditions of temperature, rate and amount of reduction, but such crystals are always heavily twinned and are not suitable for the study of the properties of single crystals. By progressive solidification from the molten state untwinned crystals of copper are obtainable and the mechanical properties of these have been studied by Elam²³ and by Güler and Sachs.²⁴ According to the latter workers, the yield point in tension depends on the orientation of the crystal in relation to the stress but corresponds to a definite shear stress of about 570 psi. on the 111 plane most favorably placed for slip. Slip is confined to this plane until the crystal has rotated sufficiently to bring another 111 plane to make an equal angle with the direction of stress, when slip proceeds along both planes simultaneously, the crystal orienting itself with the 121 axis parallel to the direction of the stress.

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Properties of Commercially Pure Copper

By H. C. Jennison† and Cyril Stanley Smith*

In the article on the Physical Constants of Copper, page 1380, are given the properties of the substantially pure element. Many of the figures were actually determined on good grades of commercial copper, which is always of high purity except for the presence of oxygen and does not differ greatly in many of its properties from absolutely pure copper. The present article discusses the various grades and forms of commercial copper and their mechanical properties, together with the influence of the various impurities or intentional additions that are often encountered and the effect of such mechanical and heat treatments as are customarily given.

Grades and Composition—The principal grades of copper at present in use in the United States are Electrolytic, Lake, Lake Arsenical, Casting, Deoxidized, and various forms of oxygen free copper. By far the greatest amount of copper used in this country is electrolytic. In England an additional grade known as "Best Select" is used for many purposes. Both the American Casting copper and the English Best Select are fire refined and contain more impurities than the electrolytic grades. Statistics regarding the production of the various grades of copper are given in the article on Copper Industry, page 1339, and are annually published by the American Bureau of Metals Statistics.

Typical compositions of some of the principal grades of copper are given in Table I.

Table I
Typical Analyses of Copper

Elements	Cathode Copper*	Electrolytic Wire Bar, U. S.*	Electrolytic Wire Bar, Chile*	High Conductivity, Lake†	Arsenical, Lake†	Phosphorized Copper*	Oxygen Free Copper†
Ag	0.0001	0.0001	0.0001	0.03	.....	.....	0.002
O	0.0000	0.0350	(0.032)	0.0420	0.0400	0.0000	0.0000
S	0.0032	0.0021	0.0023	0.0015	0.0015	0.0016	0.0025
Fe	0.0010	0.0026	0.0037	0.0025	0.0025	0.0013	0.0015
As	0.0002	0.0009	0.0005	0.0025	0.04	0.0005	0.0008
Sb	0.0005	0.0009	0.0004	0.0005*	.....	0.0010	0.0028
Bi	0.0000	0.0000	0.0000	0.0000*	.....	0.0000	trace
Pb	0.0003	0.0014	0.0002	0.0006*	.....	0.0003	0.0004
Ni	0.0013	0.0021	0.0005	0.0015	0.0015	0.0016	0.0016
Se and Te.....	0.0000	0.0002	0.0006	0.0000*	.....	0.0032	0.0031
P .....	.....	.....	.....	.....	.....	0.020	0.0000
Si .....	.....	.....	.....	.....	.....	.....	0.0015
Recrystallization, temp. (approx.)	.....	200	.....	350	350	.....	275°C.
Conductivity, % (approx.)	102	100.5	101.0	100.0	88	80	100.5

*American Brass Co. analyses.

†Analyses given by Lovell and Kenny*.

‡Analysis given by Webster, Christie, and Pratt*.

Electrolytic Copper—Electrolytic copper, as its name implies, is produced by electrolysis from relatively impure fire refined anodes or deposited directly from a solution containing copper leached from the ore. About 23% of the cathodes produced are sold as such and are used in the manufacture of copper alloys, but the greater proportion of the electrolytic copper of commerce is remelted or "refined". The latter process comprises the well known operations of oxidation to remove sulphur and other elements adsorbed on the cathodes or absorbed during melting and poling with green wood poles, which reduces the oxygen content to the correct amount. By electrically melting cathodes under proper conditions it is possible to avoid contamination by sulphur or gases and to pour tough pitch copper directly with no delay due to flapping and poling operations. This process has been made continuous. Electrolysis is necessary in the production of high purity copper only in the presence of objectionable impurities in the ores which cannot be removed by fire refining, or when, as is frequently the case, the extraction of precious metals contained in the blister copper more than pays for the cost of electrolytic separation. Much copper that is equal in quality to electrolytic metal is made from high grade ores entirely by fire refining operations.

†Deceased. *Research Metallurgist, American Brass Co., Waterbury, Conn.

Wire bar or ingot copper contains from 0.01-0.07% oxygen, usually about 0.04%. It is usual to judge the quality of tough pitch copper by the appearance of the "set surface" (the top surface of the casting exposed to the air during solidification), and an important part of the art of the refiner lies in balancing the oxygen and gas contents of the metal so that the gas liberated by reaction during solidification exactly balances the normal shrinkage which would occur due to the difference in density between liquid and solid copper. The correct set of tough pitch copper is approximately level with shallow wavy furrows regularly spaced over the surface. Copper with a rough convex surface is "overpoled" which indicates usually too little oxygen and always too much gas or sulphur. A concave, depressed, surface results from a high oxygen content under normal conditions of pouring. The set surface is modified by the dimensions and shape of the casting.

The density of cast tough pitch copper is 8.4-8.7 g. per cc. depending on the shape of the casting and the proportion of set surface. This density corresponds to the presence of about 3-5% of voids or gas holes, which in properly refined copper are small and distributed uniformly throughout the cross section of the casting. They are completely closed up during rolling. After working and annealing to produce maximum density, copper containing about 0.03% oxygen has a density of about 8.92, but this depends on the oxygen content.

Lake Copper—Lake copper, which constitutes about 10-15% of the United States output, derives its name from its origin in the Lake Superior region. It is not electrolytically refined, but is of high purity and if free from arsenic has an electrical conductivity equal to that of electrolytic copper. It differs from electrolytic copper in that it may contain small amounts of silver or arsenic. When arsenic is desired it may vary from 0.04-0.3% or even higher to suit the purpose for which the copper is intended. Arsenical and argentiferous coppers are not infrequently made synthetically from electrolytic copper.

Deoxidized Copper—Deoxidized copper is made by adding a strong reducing agent such as phosphorus or silicon to molten tough pitch copper, either to a ladle of metal removed from the refining furnace or to a crucible charge of remelted copper. The function of the reducing agent is to remove the residual oxygen present in all tough pitch copper. Deoxidized copper always shrinks deeply, forming a "pipe" that must be discarded or eliminated by feeding with molten metal. It should have a density of 8.8-8.9 g. per cc. or higher.

Deoxidized copper usually has a comparatively low electrical conductivity on account of residual amounts of the deoxidizing element. When a high conductivity is required, calcium,³ lithium,⁴ calcium boride or beryllium is sometimes employed as a deoxidizer. A commercial grade of phosphorized copper is available, made under controlled conditions so that the residual phosphorus content is below 0.005% and the conductivity will meet A.S.T.M. specifications for high conductivity copper, although it is fully deoxidized.

Oxygen-Free Copper—Oxygen-free copper is a commercially pure copper made by casting under conditions which prevent absorption of oxygen. Its conductivity is equal to that of

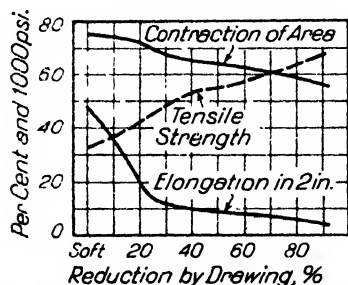


Fig. 1—Characteristic drawing curves of tough pitch copper.

tough pitch copper. A process has recently been introduced for continuous casting in which copper is withdrawn through a die and more molten metal introduced at the same rate that it solidifies. It is reported that the directional solidification results in unusually high density. Another new variety of oxygen-free copper is made by compressing broken brittle cathodes in a reducing atmosphere when hot and extruding them to bars without melting. All these methods have for their object the conversion of the copper cathodes with a minimum of contamination into a form fit for further work.

Both deoxidized and oxygen-free copper are used for applications where the presence of oxygen is harmful, as for example when a copper of exceptionally high ductility is required, when the copper is to be welded, or when it has to be heated in a reducing atmosphere. The absence of oxygen increases ductility particularly as

enhances the capacity for undergoing severe cold working operations. The hot ductility of tough pitch copper decreases to a minimum at temperatures ranging about 500°C. but in phosphorized copper this is much less marked.*

Gassing of Copper—When copper containing oxygen is heated for a sufficient time in a reducing atmosphere at temperatures above about 400°C. it becomes severely embrittled. Deoxidized or oxygen-free copper is not embrittled under the same conditions. This effect, which was first adequately described by Dick²⁰ in 1856, is due²¹ to the reaction between copper oxide and the reducing gases, which diffuse into the solid copper more rapidly than the gaseous reaction products can escape. The local high pressures developed actually blow the copper apart at the weakest points, which, at the temperatures considered, are the grain boundaries. A very slightly reducing atmosphere will cause trouble, as for example that resulting from traces of oil or even from the presence of steel on heating in a closed space. Such embrittlement never occurs during the fabrication of copper under proper conditions but is sometimes encountered when copper is employed in locations where a reducing atmosphere is unavoidable. In this case, deoxidized or oxygen-free copper should be employed, but it should be noted that when either deoxidized or oxygen-free copper is heated in an oxidizing atmosphere diffusion of oxygen will occur with the effective removal of the deoxidant in the surface layer and it is therefore important to avoid prolonged alternate treatment in oxidizing and reducing gases. Copper deoxidized in different ways differs considerably in its susceptibility to embrittlement by such treatments.*

Forms of Commercial Copper—Copper for remelting or alloying is sold in the form of cathodes, ingots, or "warmer bars". Commercial copper for rolling, with which this article is primarily concerned, is cast in the refinery in the form of wire bars, cakes, slabs, and billets of well defined standard shapes and weights. These castings are usually made directly from the refining furnace on a casting machine and are made in open molds of copper with the surface of the metal exposed to the air.

Wire bars for rolling to rod and drawing to wire customarily weigh 200-300 lb., although larger and smaller sizes are frequently cast. A 300 lb. bar is 54 in. long, 4½ in. high and tapers from 4 in. wide at the bottom to 4½ in. wide at the top. Both ends of the bar are usually pointed to facilitate rolling. The bars are cast horizontally and the top surface is exposed to the air during casting. Sometimes the oxidized set surface is removed by milling, or a special vertically cast wire bar with the set surface on the end may be used.

Cakes and slabs are used principally for rolling to sheet. They are approximately rectangular in section and of various shapes and sizes according to the product being rolled. In many cases they are poured on edge ("wedge cakes") or on end so that the set surface is on an unimportant part of the product being rolled, or may easily be trimmed off.

Billets are round bars cast on end. These may be from 2-10 in. dia. and vary in weight from 75-750 lb. They are used principally for piercing in the manufacture of seamless tubing and are usually of deoxidized copper. Some billets are used for extruding in the manufacture of rods and various shaped sections.

In addition to the cast shapes mentioned above and many special cast shapes, copper may be obtained for engineering uses in a wide range of semifabricated forms such as rod, bars, wires, tube, plate, and sheet, extruded and rolled sections of innumerable shapes and sizes.

Table II
A.S.T.M. Specification Values for the Tensile Properties of Copper Wire

Dia.	Hard Drawn Wire		Medium Drawn Wire			Soft Wire	
	Min. Tensile Strength, psi.	Min. Elongation on 60 in., %	Min. Tensile Strength, psi.	Max. Tensile Strength, psi.	Elongation on 60 in., %	Max. Tensile Strength, psi.	Min. Elongation on 60 in., %
0.480	49,000	3.75	42,000	49,000	3.75	36,000	35
0.204	60,100	1.24	48,330	55,330	1.25	37,000	30
0.128	63,700	1.02	49,660	56,660	1.08		
0.081	65,700	0.94	51,000	58,000	1.00	38,500	25
0.040	67,000	0.85	53,000	60,000	0.88		
Electrical resistivity (max.) ohms per m.g.	910.15		905.44			891.58	
Electrical resistivity, microhm per c.m.	1.7930		1.7837			1.7564	

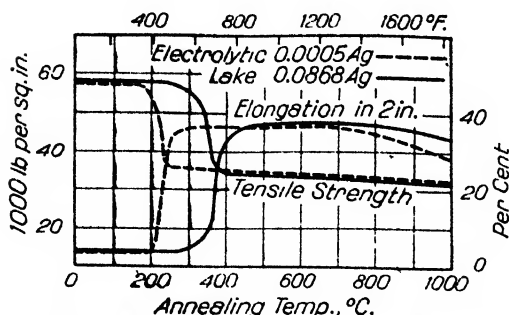


Fig. 2—Effect of silver on annealing of copper (0.05 in. sheet). (Bassett and Davis.)

pose it is important that the furnace atmosphere be maintained neutral or oxidizing to avoid the action known as "gassing," which produces severe cracks in the surface.⁸

Sheet copper is sometimes used as it comes from hot rolling, but it is more commonly employed after it has been cold worked to increase its hardness and tensile strength. The tensile strength of hot rolled or annealed copper is about 30,000-36,000 psi., but this can be increased to almost 70,000 psi. by extensive cold working; this, however, is at the expense of some ductility.

Fig. 1, taken from the paper by Webster, Christie, and Pratt,¹¹ shows the variation of the tensile properties of tough pitch copper as it is cold worked to an increasing extent. The tests were made on wires drawn from 0.5 in. to successively decreasing diameters and show clearly the hardening effect due to cold working. Table II gives the A.S.T.M. specifications¹² for wire of different diameters and indicates the range of properties normally obtainable in commercial copper wire. It is not practical to perform extensive cold work on the larger sizes of wire, and for this reason the strength decreases as the section of the cold drawn wire increases. Cold rolling has a similar effect in increasing the strength and decreasing the ductility of copper sheet or strip.

The importance of several factors in affecting the change of properties during the cold working and annealing of copper has been studied by Mathewson and Thalheimer,⁹ Caeser and Gerner,¹⁰ Webster, Christie, and Pratt,^{11, 7} and others.

The increased hardness and strength due to cold work may be completely removed by annealing at a temperature above the "recrystallization temperature". This temperature is affected by the presence of even small amounts of impurities, particularly silver, antimony, and arsenic, and varies both with the amount of cold work which the copper has undergone and the length of the annealing operation. A curious fact is that in spite of its high purity the recrystallization temperature of "oxygen-free" copper is higher than ordinary electrolytic tough pitch copper.⁷

The different behavior on annealing of an electrolytic and a Lake copper with different silver contents is shown clearly in Fig. 2 (Bassett and Davis¹²). The two grades of copper are not greatly different in properties either in the worked condition or when fully annealed, but the temperature at which the rapid decrease in strength and increase in ductility occurs is different for the two grades.

Under extended periods of annealing perfectly pure copper will recrystallize at about 212°F., but the impurities in commercial copper usually prevent substantial softening at this temperature. In cases where slightly elevated temperatures are to be encountered in service and the superior properties due to cold working are desired, the importance of selecting a grade of copper with high recrystallization temperature will be obvious. The most common of such applications are for parts to be tinned or soldered, for engraver's plates, and, to some extent, for fire box plates and stays. For these purposes Lake copper or a natural or synthetic antimony or silver-bearing copper should be used.

Under normal conditions rolled copper will have small grain size (about 0.02-0.05 mm. dia.) and will not possess any marked directional properties due to a preferred orientation resulting either from cold working or from annealing. Under certain highly critical conditions of hot rolling large grains may form, and after extensive cold working considerable difference in properties in different directions may result. This becomes more pronounced on annealing at the high temperatures, but it is not a characteristic of correctly fabricated material.

Rolling—Copper is malleable at any temperature up to about 1050°C. The normal temperature for starting the hot rolling of copper for wire rod or sheet is about 850°C., and the finishing temperature may be as low as 400°C. The temperature of rolling is less important than that for other hot working processes, for example piercing or extruding, in both of which the temperature of the billets must be closely controlled. When heating tough pitch copper for rolling, annealing, or for any other purpose

After a careful study of all published values, Gillett¹⁴ concludes that the endurance limit of annealed commercial tough pitch copper rod is about 10,000 psi., as measured by the rotating beam test. Cold working increases this to values as high as 20,000 lb. Tests show that 15,000 psi. is a conservative value for commercial tough pitch copper in the cold drawn condition, but this will be changed by the presence of impurities.

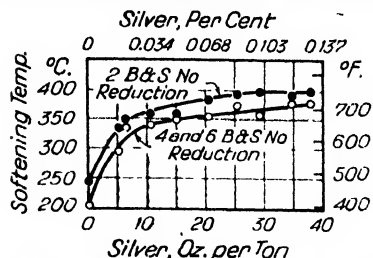


Fig. 3—Effect of silver on annealing temperature of cold rolled copper sheet.

established in 1913 to represent the average of the best commercial material then being produced. Since that time refining methods have improved, and it is not at all unusual to find copper with a conductivity of over 101%, and occasionally as high as 102% of the standard. This standard corresponds to a resistance of 0.15328 ohm (m.g.) at 20°C., and the density is assumed to be 8.89 g. per cc. This is equivalent to a resistance of 1.7241 microhm-cm., or a conductivity of 58.0 ohms⁻¹ (m., mm.²) at 20°C. A.S.T.M. specifications for Electrolytic and Low Resistance Lake copper,^{1,2} call for a resistivity not exceeding 0.15436 ohm (m.g.) at 20°C., that is, a conductivity not less than 99.3% I.A.C.S.

The electrical resistance of copper increases with temperature, the constant mass coefficient at 20°C. being about 0.00393 per °C. At 100°C. the conductivity is thus only about 76% of the conductivity at 20°C. The temperature coefficient at 20°C. is approximately directly proportional to the actual value of the conductivity.

Severe cold working decreases the electrical conductivity about 3%, but the factor of greatest importance is the presence of impurities. As little as 0.02% phosphorus reduces the conductivity 20%, although 0.2% of oxygen reduces the conductivity only about 2%. The elements are approximately in the following order in their effects in small amounts^{15, 16, 17, 18}: Phosphorus, silicon, arsenic, iron, beryllium, manganese, aluminum, antimony, nickel, tin, zinc, gold, cadmium, sulphur, silver, oxygen, and lead. The effect of many of these elements depends on the amount of oxygen in the copper.

The thermal conductivity of copper, of electrical conductivity equal to 100%, International Annealed Copper Standard, is about 0.93 cal./cm.²/cm./sec./°C. The presence of impurities decreases the conductivity considerably but somewhat less rapidly in proportion than the electrical conductivity. The ratio between the two conductivities depends on the actual value of the conductivity, but is relatively independent of the composition.¹⁹

The Effect of Impurities on Copper—A detailed study of the effect of impurities on the mechanical and electrical properties of copper has been made by the British Nonferrous Metals Research Association.²¹ The results have been published on oxygen,²¹ iron,²² bismuth,²³ arsenic,²⁴ phosphorus,²⁵ and antimony.²⁶ An excellent summary of the properties of argentiferous and arsenical copper is given in the book by J. L. Gregg.²⁰

Oxygen²¹ is present in all commercial copper except in deoxidized and some other special grades. It exists in the casting as a copper-copper oxide eutectic and in worked copper in the form of small globules of Cu₂O, visible under the microscope. Its effect on the mechanical properties is not great, although it reduces the ductility as shown by the reduction of area in the tensile test, and slowly increases the tensile strength. The first additions of oxygen in commercial copper often have the effect of increasing the electrical conductivity, probably due to the partial oxidation of other impurities which are thereby removed from solid solution, but large amounts of oxygen slowly reduce the conductivity by reducing the effective cross section of metal.

Sulphur,^{22, 23} selenium,²² and tellurium²³ are generally regarded as being extremely harmful to copper but this is actually the case only in tough pitch copper, and possibly only sulphur is harmful there. Amounts up to about 1% of selenium and tellurium may be used for the purpose of promoting machinability without the hot shortness concomitant with lead. These elements exist in the form of eutectics

of copper with Cu_2S , Cu_2Se , or Cu_2Te similar to the copper oxide eutectic, and have a similar effect on the mechanical properties.

Bismuth² is almost completely insoluble in copper and promotes brittleness if in amounts over about 0.001%. The solubility of bismuth varies with temperature, and by quenching from a high temperature bismuth up to 0.006% may be rendered harmless in arsenical copper (Blazey³). Bismuth is rarely encountered in detectable amounts in American copper. Its effects may be partly neutralized by additions of suitable corrective elements, such as oxygen, arsenic, and antimony.¹

Antimony² is sometimes added to copper where a high recrystallization temperature is desired. In amounts of 0.5% and even higher it slightly hardens copper and decreases the ductility, but it cannot be considered a harmful impurity except where the highest conductivity is required. The presence of antimony is extremely harmful to brass, and antimony-bearing scrap copper is anathema in the brass mill.

Arsenic² occurs naturally in Lake copper and may be allowed to remain after refining in amounts up to 0.3% or higher. It is often added intentionally in amounts to 0.6%, particularly in European coppers. It has a small hardening and strengthening effect, especially in the cold worked condition, raises the recrystallization temperature, but is practically without effect on ductility. It decreases the conductivity considerably.

Silver is, after oxygen, the most common element that occurs in appreciable quantity in commercial copper. It has rather small effect on the mechanical properties and electrical conductivity, but has as great an effect on the recrystallization temperature as any element. The effect is clearly shown in Fig. 3, taken from the paper by Kenny and Craig.²

Iron² is normally present in copper only in small amounts which are totally without effect on the mechanical properties. Added in amounts up to 2% it hardens and strengthens copper slightly without destroying the ductility and reduces rapidly the electrical conductivity, particularly in the absence of oxygen, which lessens the effect. Copper and most of its alloys containing even traces of iron become feebly ferromagnetic on cold working, but annealing renders them nonmagnetic again.

Lead should be present in amounts not over 0.005% if copper is to be hot rolled, although in much larger amounts it has little effect on the ductility of copper at room temperatures. It can be rendered less harmful by the presence of oxygen.

Cadmium is rarely present in commercial copper, except when it is intentionally added in amounts of about 0.7-1.0% for the production of an alloy of high strength with good conductivity which finds extensive application for trolley wire. Strengths as high as 92,000 psi. with an electrical conductivity of 80% I.A.C.S. are readily obtainable in the cold drawn alloy.

Gases—The influence of gas in copper is a complex problem of greater importance to the producer of copper castings than to the user. The level set of tough pitch copper is believed by Allen² to be due to the liberation of H_2O or other insoluble gas by reaction as the oxygen concentration increases as the crystals progressively solidify. The amount of gas evolved should exactly neutralize the natural shrinkage of the metal on passing from the liquid to the solid state. Hydrogen is very soluble in liquid copper but will not cause unsoundness in copper castings in the absence of oxygen unless the solubility in the solid state, which is high, is exceeded. Carbon monoxide is probably soluble in solid and liquid copper to about the same extent and in the absence of oxygen is not harmful. Carbon dioxide and nitrogen both behave as if they were insoluble in copper.

Many other elements are intentionally added to copper for the formation of alloys. The elements listed above and those used as deoxidizers are practically all that are encountered in the various alloys which pass under the name of commercial copper and whose effects as impurities are important.

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Properties of Copper-Zinc Alloys

(Commercial Brasses)

By D. K. Crampton*

The copper-zinc alloys, known as the brasses, form one of the most useful groups of alloys known to industry. These alloys are characterized by unusual ductility and malleability, good strength, excellent corrosion resistance, pleasing color, and other desirable properties. Many special or complex brasses, containing various alloying elements in addition to copper and zinc, are produced commercially, but the present article is confined to consideration of the common brasses, binary copper-zinc alloys.

The useful wrought alloys cover a wide range of composition, the copper content extending from about 55 to almost 100%. The range of properties is correspondingly great, making them suitable for a wide variety of uses. Fig. 1-6 and Table II give general properties for alloys ranging from about 60% to about 100% copper.

All the alloys may be cold worked, but some to a great degree. Alloys throughout the range may be hot worked, those with copper contents up to 65% and from 85-100% being capable of extensive hot working. Strength, for a given treatment, increases as copper content decreases.

Greenall and Gohn¹ have published data on fatigue or endurance properties of several brasses, which show that the endurance limit of 65-35 brass sheet increases from about 14,000 psi., annealed, to about 20,000 psi. as rolled 8 or 10 B & S numbers hard. Corresponding values for 72-28 brass are very slightly higher. Unpublished work indicates that the endurance limit of 85-15 brass (red brass) is still higher, the value for such material as rolled 8 B & S numbers hard being about 24,000 psi.

Toughness or impact strength for annealed material is quite generally high over the range of commercial alloys, increasing with zinc content to a maximum value at about 30% zinc and thereafter decreasing, the lowering of toughness becoming more pronounced with the appearance of the beta phase. The effect of cold working is to reduce toughness, this effect apparently being more severe in the alpha range of alloys than in the alpha plus beta range. These various points are illustrated in Table I.

Table I
Tensile Impact Values for 0.102 in. Wire
(Specimens 4.1 in. between grips)

Name	Composition, %		Temper	Tensile Impact Energy, ft. lb.
	Copper	Zinc		
High conductivity phosphorized copper	99.95+	(P0.01)	Annealed, drawn 60%	37
Cartridge or spinning brass.....	70	30	Annealed, drawn 60%	88
Muntz metal.....	59	41	Annealed, drawn 60%	13
				68
				28

The color is pleasing in all cases. Small percentages of zinc have practically no effect on the red copper color, but with 10% zinc a true bronze color is obtained. This merges into a red gold color at 20% zinc. With increasing zinc the color changes further, and 25-38% zinc produces the typical yellow brass color. From 38-45% zinc, the alloys take on a somewhat reddish cast.

The widespread use of the brasses is to a great extent due to their resistance to corrosion. The resistance of the entire range of alloys is good, but the optimum properties are probably found in the vicinity of 85% copper and 15% zinc.

All the alloys are machinable, although usually considered "tough" in machining, due to the tenacity of the chips. Machinability increases as the copper content decreases, the better machining alloys being those with from 55-63% copper. Where

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¹C. H. Greenall and G. R. Gohn, Fatigue Properties of Nonferrous Sheet Metals, Proc. A.S.T.M., 1937, v. 37, pt. II, p. 160.

Table II
Composition and General Properties of Brasses

Name	Composition, % Copper Zinc	Typical Uses	Forms for Which Properties Are Given	Temper	Rockwell Hardness F B	Tensile Strength, psi.	Elongation in 2 in., %
Muntz metal	59 41	Architectural work, welding rod, condenser tubes, valve stems	0.040 in. sheet 0.040 in. sheet	Hot rolled Cold rolled	80 ..	54,000 80,000	45 5
Extruded rivet metal	63 37	Rivets, screws	0 100 in. wire	Rivet	.. ..	60,000	30
High brass	66 34	Stamping, blanking, drawing, spin- ning, forming, radiator cores, springs, screws, rivets, drawn shapes, grillwork, chain	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.100 in. wire 0.100 in. wire	Light anneal Soft anneal Hard Spring Rivet Spring	78 .. 60 .. 85 .. 90	53,000 46,000 76,000 92,000 60,000 125,000	54 64 7 3 30 ..
Cartridge or spinning brass	70 30	Cartridges, musical instruments, eyelets, tubes, spinning, drawing	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet	Light anneal Soft anneal Hard Spring	78 .. 60 .. 85 .. 90 ..	53,000 46,000 76,000 92,000	54 64 7 3
Brazing brass	75 25	Drawing, spinning, eyelets, springs, musical instruments. Particularly suited for brazing	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.100 in. wire	Light anneal Soft anneal Hard Spring Spring	77 .. 58 .. 85 .. 90	52,000 45,000 76,000 92,000 125,000	50 62 7 3 ..
Low brass	80 20	Drawing, forming, ornamental and architectural work, clock dials, flexible hose	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.100 in. wire	Light anneal Soft anneal Hard Spring Spring	75 .. 60 .. 83 .. 90	47,000 43,000 75,000 91,000 120,000	47 55 7 3 ..
Rich low brass	83 17	Fourdriner wire	0 100 in. wire	Soft	.. ..	42,000	..
Red brass	85 15	Hardware, radiator cores, plumb- ing pipe, condenser tubes, flexible hose	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet	Light anneal Soft anneal Hard Spring	71 .. 56 .. 78 .. 85 ..	45,000 40,000 71,000 83,000	43 48 5 3
Commercial bronzes	90 10	Screen wire, hardware, trim, forg- ings, screws, rivets, costume jewelry	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet	Light anneal Soft anneal Hard Spring	62 .. 50 .. 74 .. 80 ..	41,000 38,000 64,000 75,000	42 45 4 3
Golding metal (commercial bronzes, 95%)	95 5	Drawing, spinning, forming	0.040 in. sheet 0.040 in. sheet 0.040 in. sheet 0.040 in. sheet	Light anneal Soft anneal Hard Spring	55 .. 45 .. 72 .. 77 ..	38,000 36,000 56,000 66,000	42 44 4 3

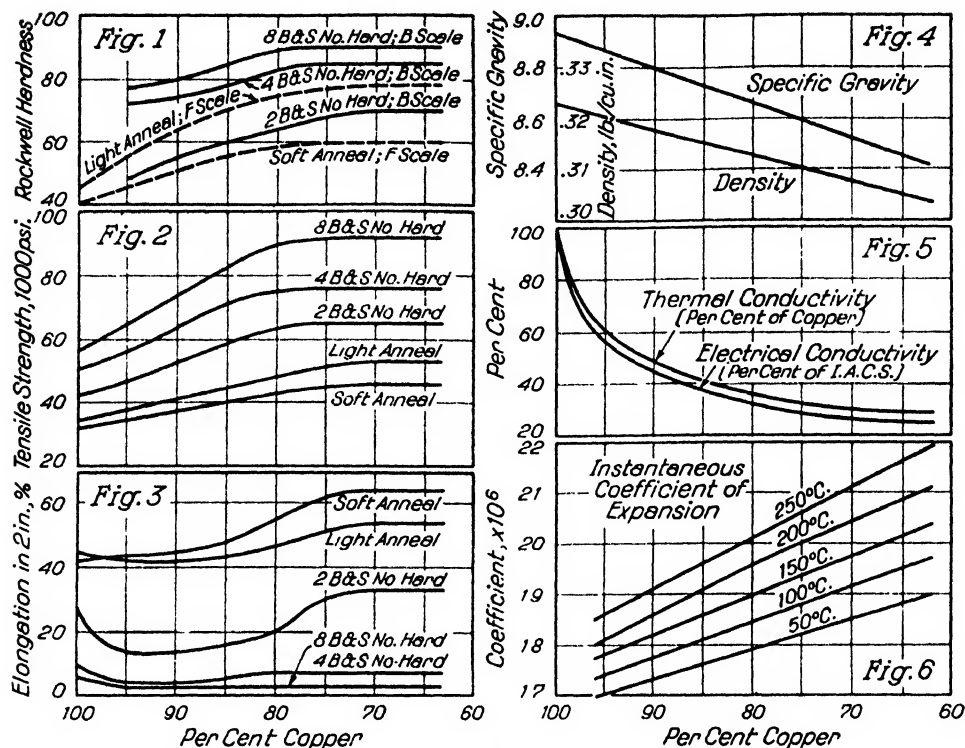


Fig. 1—Rockwell hardness of copper-zinc alloys (0.040 in. sheet).

Fig. 2—Tensile strength of copper-zinc alloys (0.040 in. sheet).

Fig. 3—Elongation of copper-zinc alloys (0.040 in. sheet).

Fig. 4—Specific gravity and density of copper-zinc alloys.

Fig. 5—Electrical and thermal conductivity of copper-zinc alloys (C. S. Smith).

Fig. 6—Thermal expansion of copper-zinc alloys (Bureau of Standards Sci. Paper, 410).

really good machinability in desired, one of the several available lead-bearing brasses should be employed in preference to any listed here.

While brasses of all copper contents within the total range are useful ones, a few of definite composition have come to be standardized in commercial practice. These are usually referred to by generally recognized names and are to be preferred to slight modifications which do not increase their usefulness and only complicate production schedules. Table I outlines the names and compositions of the preferred alloys, their general properties, and typical uses.

Properties of Wrought Copper-Zinc Alloys (66-34 Brass)

By R. S. Pratt*

General—The copper-zinc alloys form ductile solid solutions with additions of zinc up to 36%¹ or with copper contents from 100-64%. With a zinc content of over 36% a second solid solution is formed which is appreciably less ductile in cold working. The 66-34 alloy is made commercially with a copper content between 64.5 and 67.5% and, therefore, represents about the lowest possible copper content in those alloys which contain simply the ductile alpha solid solution.² Because of this fact, the alloy has been well known as "common high brass" and is the cheapest alloy which is suitable for the more severe cold working, heading, cupping, forming, and spinning operations.

With the nominal 66-34 alloy, the second solid solution beta is never found except in the cast condition or in exceptional cases of severe overheating. When the copper content runs as low as 65%, however, the beta constituent is quite often found, particularly after a hot working operation has been used to break down the metal from the cast form. Proper annealing treatment will remove the beta constituent³ and it is, therefore, customary to regard the common high brass alloy as one purely of the alpha solid solution.

General Properties—The more general properties of the alloys are given in Table I.

The copper-zinc alloys are well known in general and there is much in the literature concerning them. There is, however, considerable confusion in many references as to the exact analysis, because many variations and types of alloys have been tested rather than concentrated work on a particular alloy.

Commercial Alloy of High Brass—The commercial limits quoted are of interest in understanding the comparatively wide range of alloys generally classified as high brass. Accepting these limits, the resulting range of properties due to variation in mixture is more or less apparent. For this reason, only the more important of the general physical properties are given in Table I.

Density—Hidnert⁴ gives some excellent data on the densities and coefficients of linear expansion of the copper-zinc alloys, including the 66-34 alloy. The density figure given in Table I checks the work of Bamford⁵ on a chilled cast alloy of the same mixture.

Table I
General Properties of High Brass

Commercial mixture limits, per cent.....	64.5-67.5 copper, 0.30 lead max., 0.07 iron max., zinc remainder
Melting range.....	1660-1715°F., 905-935°C.
Crystal structure.....	Face-centered cubic
Density at 20°C.....	8.47 g. per cm. ³
Weight per cu.in.....	0.306 lb.
Linear coefficient of expansion (25-300°C.).....	0.0000201 per °C.
Thermal conductivity at 20°C.....	0.286 cal. per sq.cm. per cm. per sec. per °C.
Specific heat at 18°C.....	0.0909 cal.
Electrical resistivity at 20°C.....	40.12 ohms per circular mil-ft., 6.68 microhms per cm. ²
Electrical conductivity at 20°C.....	25.85% (copper 100%)
Modulus of elasticity.....	15,000,000 psi.
Tensile strength—Annealed.....	40,000-50,000 psi.
Cold worked.....	50,000-140,000 psi.
Endurance Limit—Annealed.....	10,000-15,000 psi.
Cold worked.....	13,000-20,000 psi.

Coefficient of Expansion—The linear coefficient of expansion quoted covers the range between 25-300°C., but in Hidnert's⁴ paper it is given for each range of 100° between 25 and 300°C. It is interesting to note that these figures show an increasing coefficient with increasing temperature.

Thermal Conductivity—C. S. Smith⁶ gives the thermal conductivity of the copper-zinc alloys. In general, his values are higher over the range of alloys than those of the earlier workers on the same subject. Sedstrom⁷ gives a figure of 0.265

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cal. per sq.cm. per cm. per °C. per sec. for the 67-33 alloy, while Smith gives 0.288 cal. for a 65.5-34.5 alloy. Smith also reports a positive temperature coefficient of 0.001049 cal. per °C. at 20°C. for the latter alloy.

Specific Heat—Doerincel and Werner⁸ report a number of figures for specific heat of the copper-zinc alloys. A formula is given which is purported to give the specific heat at any temperature for a 67-33 alloy based on a straight line relationship between temperature and specific heat values. At the melting point, the specific heat may be computed to be about 0.11 cal. The value for specific heat at 0°C. is given in the Smithsonian Physical Tables as 0.0883.⁹

Electrical Resistivity—In the data sheet on copper alloys in Kent's Mechanical Engineers Handbook written by W. H. Bassett¹⁰ there is an excellent list of the resistivities of the whole series of copper-zinc alloys, apparently taken from determinations in his laboratory. The values quoted in Table I are taken from that table, although some determinations made in the author's laboratory show higher resistances. The International Critical Tables¹¹ report resistances of 6.302, 6.72 and 7.029 microhms per cu. cm. for alloys of this type as compared with the value of 6.68 microhms per cc. given in Table I.

Modulus of Elasticity—The data on modulus of elasticity for high brass are rather limited. Determinations made in the author's laboratory have shown a modulus of about 15,000,000 psi. with various samples and testing conditions. Townsend and Greenall¹² report a value of 14,500,000 psi. for this property.

Endurance Limit—The data on endurance limits of this alloy have been obtained from various sources. Dr. McAdam¹³ reported an endurance limit for annealed high brass slightly higher than for moderately cold worked material. The value for the annealed material was about 15,000 psi. and for the cold worked material from 13,000-17,000 psi. Townsend and Greenall¹² give 11,000 psi. as the endurance limit of annealed sheet brass and 13,000-15,000 psi. for rolled sheet brass.

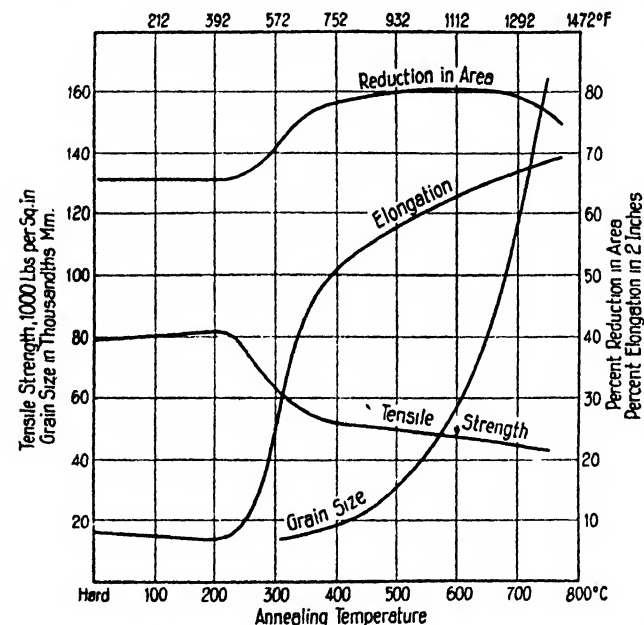


Fig. 1—Effect of annealing temperatures on the properties of high brass.

Mechanical Properties—High brass, in common with most metals, hardens on cold working, which makes it necessary to anneal before further cold working may be done. The temperature and time of annealing are of primary importance in controlling the properties of the metal, and a knowledge of their effect is necessary in order to have an understanding of the properties which may be obtained.

When cast, the metal is fairly soft and ductile, but has a tensile strength and ductility appreciably lower than in the worked and annealed condition. The structure is not homogeneous, but contains some portions which are higher in zinc content than others and quite often it contains small amounts of porosity due to difficulties in the casting operation.

Annealing—The metal is annealed after casting to produce a homogeneous structure and is then cold rolled or drawn. In some cases it is possible to perform a

cold working operation before annealing which is advantageous in producing the homogenized structure. The metal may be hot worked if the impurities usually present are held to a minimum.¹⁴ When the metal hardens so that further cold rolling becomes impractical, it is then annealed to prepare it for further cold working. In annealing, the metal softens or recrystallizes at a temperature ranging from 475-650°F. (250-350°C.). The exact temperature depends on the amount of cold working prior to the annealing and the degree of annealing prior to the cold working operation.¹⁵

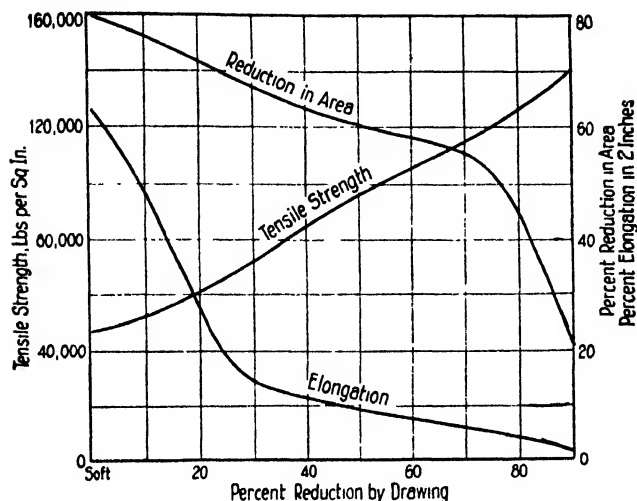


Fig. 2—Effect of cold drawing on the physical properties of high brass.

ber of investigators have reported a slight rise in tensile strength at temperatures below the recrystallization range,¹⁶ but it has not been possible to produce metal commercially so as to take advantage of this fact. These points are brought out graphically in Fig. 1.

Effect of Annealing Time—Considerable work has been done on the effect of time in annealing which would indicate that increasing the time will tend to soften the metal the same as does increasing temperature, although not to so marked a degree. This problem is brought out commercially in some types of electric annealing where a short time at high temperatures takes the place of lower temperatures for much longer periods of time. Commercially, the time element in annealing includes the time required to attain the desired temperature. In such cases, the time is of importance inasmuch as it indicates whether or not the metal has attained the desired temperature.

Effect of Cold Working—When the metal is fully annealed, it is ready for additional cold working and it is interesting to note the effect of various amounts of cold working. The first result is an increase in the tensile strength of the material and a very marked decrease in its elongation^{17, 18} with a somewhat slighter decrease in reduction of area. The rate at which reduction of area decreases with the amount of cold rolling or drawing is an excellent comparative indication of the ability of the metal to withstand successive cold working operations without failure.¹⁹ Emphasis is laid on the term comparative as, for example, the curve in Fig. 2 showing the effect of cold working might indicate that high brass is fairly ductile and capable of withstanding repeated cold working operations up to a reduction of about 70%. As a matter of fact, this figure may or may not be attained as it depends upon the method of working and the suitability of the tools used.

Effect of Impurities—High brass is made in several grades in which the difference is largely one of amount of impurities and this is controlled primarily by the purity of the zinc used. Lead and iron are the most common impurities so introduced, but occasionally small amounts of tin get into the mixture through the use

In this annealing temperature range, the tensile strength of the cold worked metal decreases to about 50,000 psi. and there is a notable increase in elongation and reduction of area. Annealing at higher temperatures results in a relatively slight further decrease in the tensile strength and is also accompanied by a more noticeable increase in elongation and reduction of area. There is also an increase in grain size with increasing annealing temperature from the minimum, which occurs immediately after complete recrystallization. A num-

of scrap containing tin. The higher grade alloys for eyelet brass and rivet wire use high grade zinc and the lead and iron contents are kept as low as 0.05% or even lower.

The effect of lead in quantities less than 0.10% does not seem to be apparent in the usual physical test data, but commercial experience would indicate that it is injurious if present in material which is required to withstand the most severe cold working operations. Lead in quantities over 0.25% has been found to aid materially when it is desired to machine articles made of high brass. Its function in this way is to break up the chips making their removal much less difficult. As the lead content is increased, the cold working becomes more difficult due to the decrease in percentage elongation and reduction of area. By compromising between the machining properties and ductility, it is possible to produce a number of valuable alloys merely by varying the lead content.

The effect of iron is much more noticeable for an equal quantity of impurity and amounts of over 0.05% decrease the grain size and increase the tensile strength appreciably. Because of this, most specifications limit the iron content to a maximum of 0.05%.

Use of High Brass—From Fig. 1 and 2, it may be seen that the properties which can be obtained in high brass cover a wide range. This accounts for the large number of uses to which it has been applied. Of all the materials used in the various fabricating plants, high brass is probably the most convenient to work with and the most simple to handle.

Large quantities of brass sheet are fabricated into a variety of articles such as electrical fittings, flashlight parts, and automobile hardware. Many of the articles are ornamental in character. High brass tubing is used in various manufactured articles and considerable pipe is made of this alloy. Large amounts of high brass wire are used in the manufacture of screws and rivets and for various heading jobs of this type.

Corrosion of High Brass—Much of the difficulty encountered in the use of high brass has been with the phenomenon known as season cracking.²⁰ Intercrystalline cracking in service, which is the same general action, occurs in several ways. It is caused by a combination of corrosion and stress, and the time element required to bring about failure is dependent on the severity of the corrosive action and the extent of the stress. Because of this, high brass, which is to be exposed to atmospheric conditions, is usually finished with a final annealing operation to relieve the internal stresses.²¹ If the corrosive action and stress are sufficiently severe the external stresses acting upon a structural member, in which the internal stresses have been relieved, are also likely to cause this type of failure.²²

It is, therefore, inadvisable to use high brass where it is subjected to severe external stress and exposure to the atmosphere. Ammonia compounds and mercuric salts are particularly active agents in causing this type of failure, and high brass should not be used where these chemicals are present.

Another difficulty encountered in the use of high brass caused by corrosion is known as dezincification. This phenomenon is usually encountered when the metal is used in contact with acids or with impure and salt bearing water. The action of a pure soft water is not injurious, but salt water and sometimes hard water are very likely to cause dezincification. The corrosion apparently proceeds by an electrolytic action which dissolves the surface at the point of contact and from the solution formed redeposits copper in a porous mass.²³ Occasionally this action will occur locally and penetrate a water tube or pipe in a very short time. In most cases, however, where soft water is to be carried, high brass can be used without danger from dezincification.

Specifications and Tests—The A.S.T.M. has developed standards for the specification and testing of sheet high brass. These standards have been changed from time to time, the most recent change being that made in 1938. These specifications (B36-38T) adopted the tensile test as the standard test for physical properties of hard rolled high brass. There are commercial objections to the use of the tensile test for control testing because of the time and expense involved in making the test. For specification work, however, no other test has been devised as yet, of as general application as the tensile test.

Above gages of about 0.020 in., the Rockwell test is generally satisfactory on hard rolled sheet. Below this gage the tensile test is the only test possible for

specification work. In the past the scleroscope test has been used for thinner gage material and is still used for control work on rolled sheets. It is subject to gage effects, however, and care must be taken in its use to make the results comparable. It is, therefore, not satisfactory for use in a general specification. Formerly the Brinell test was used in connection with the A.S.T.M. specifications but this test likewise is limited in its accuracy and usefulness to gages above 0.080 in.

Table II shows the present A.S.T.M. standards for the physical properties of rolled high brass. The specification takes care to point out that the Rockwell test values are to be used for general and approximate information only. The wide spread in Rockwell values listed are necessary, particularly in the less severely rolled material because of the effect of variations in the annealed condition before rolling. As the amount of rolling increases this effect has a lesser bearing on the ultimate Rockwell value.

In the case of annealed material, the grain size determination in acceptance standards has been adopted for the first time. Experience has increasingly shown that the grain size is the best measure of the usefulness of annealed high brass for any particular purpose because it is applicable uniformly throughout the entire range of commercial thicknesses. As an aid in controlling and checking grain size values, some data are included on the Rockwell hardness of annealed sheets. As in the case of hard rolled sheets, these values are for informatory purposes only and of the two cases the Rockwell values are more useful in the hard rolled tempers than in the annealed material. Table II shows the specified properties for annealed sheet.

Table II
Properties of Brass Sheet (A.S.T.M. B36-38T)

Temper	Tensile Strength		Rockwell Hardness*					
	psi.		"B" Scale		"F" Scale		Superficial "30-T"	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Alloys #7 and #8								
Annealed, 0.120 mm. Nom. Grain Size...	.....	.....	..	..	50	62	..	18
" 0.070 mm. " " "	.....	.....	..	..	54	67	6	27
" 0.050 mm. " " "	.....	.....	..	..	61	73	15	34
" 0.035 mm. " " "	.....	.....	..	..	65	76	23	41
" 0.025 mm. " " "	.....	.....	..	..	67	79	28	46
" 0.015 mm. " " "	.....	.....	..	..	72	85	35	53
Quarter Hard.....	49,000	59,000	40	65			25	63
Half Hard.....	55,000	65,000	57	75			54	68
Three Quarters Hard.....	62,000	72,000	68	80			65	71
Hard.....	68,000	78,000	75	85			69	73
Extra Hard.....	79,000	88,500	82	89			73	76
Spring.....	86,000	95,000	85	92			75	78
Extra Spring.....	89,500	98,500	86	93			76	79

*B and F Rockwell Hardness applies to metal 0.020 in. thick and over and 30T to hard metal 0.015 in. thick and over and annealed 0.012 in. and over.

How to Use High Brass—The question of exactly how to order high brass for any particular fabricated article is somewhat complicated. When there is a doubt as to just what to order, it is wise to take the problem up with the manufacturer and obtain the benefit of his experience.

(Continued on Next Page)

In general, articles requiring appreciable amounts of forming must be made from annealed (soft) brass. The question of the exact temper to be used is based on the amount of cold forming, the gage of the metal, and the surface required after forming. Many articles are required to withstand considerable forming without further annealing and must be in such condition after forming that they may

be readily polished. The grain size in such cases must be kept as fine as possible consistent with the forming operations, and these operations must be closely controlled so as not to stretch the metal unduly and open up the grains.

The balance between the temper of the material and the operation is a very delicate one, particularly in those cases where the forming operation will not allow ironing or smoothing the metal surface in the die. When the metal is to be given a number of draws and anneals, such as in pro-

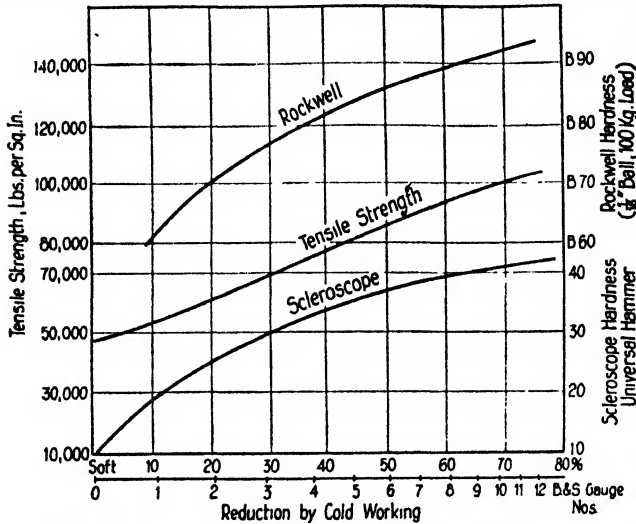


Fig. 3—Comparative hardness data on sheet high brass.

ducing a drawn shell, the grain may be somewhat coarser. Even in these cases, however, the grain must not be so coarse as to produce a rough bottom on the cupped sheet, particularly if this is to be a part of the finished article. In some cases the surface appearance is of no importance and much deeper and more severe cupping operations may be performed on the sheet if it is produced with a coarse grain.

In the case of hard metal the Rockwell test is generally used for control purposes, and here again the decision of the proper temper to be used should be based on a full knowledge of the problem. When slight forming or bending operations are to be made, the material must not be too hard. While half hard temper is usually used for this, there are some instances

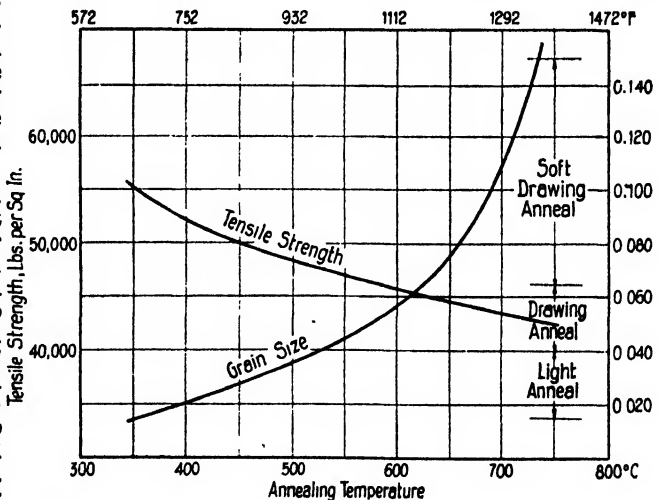


Fig. 4—Comparative test data used in controlling annealed high brass.

where even lighter tempers are required and metal less than one number hard must be furnished. When used for spring purposes or plate work, the metal must be rolled harder, depending on the surface required and, in the case of the springs or clips, the amount of bending required. It is helpful to lay out the blanking tools so that the bends will not be made parallel to the direction of rolling as the metal is much more liable to fracture if bent in this way. If it is necessary to bend the metal parallel with the grain, a less hard material must be furnished.

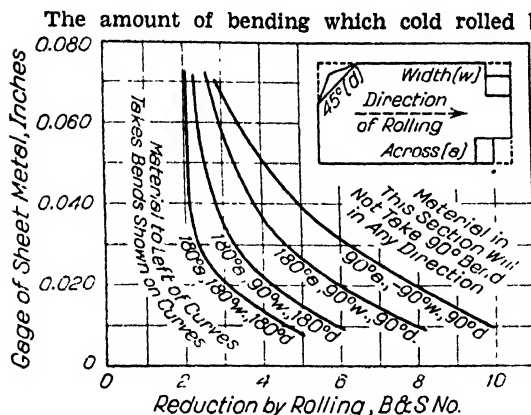


Fig. 5—Approximate bending characteristics of brass sheet.

The amount of bending which cold rolled brass will withstand depends primarily on the amount of cold rolling and, to a less degree, on the radius, and thickness of sheet. For comparative test purposes, the metal is usually bent on a radius equal to one-half the thickness of the sheet, and only sheet which has received reductions lighter than two numbers or half hard may be bent back on itself in all directions. If maximum hardness in the article is required, it is, generally, desirable to use as large a radius as possible and to make the desired bend across the direction of rolling. Fig. 5 shows some bending characteristics of sheet brass.

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Properties of 80-20 Brass

By E. S. Bunn*

General—The alloy 80% Copper and 20% Zinc, commonly called "low brass", is a single phase, golden yellow alloy. It closely resembles, in most of its properties, the more ordinarily used 85-15 or red brass.

Desired mechanical properties are obtained by combinations of cold working and annealing. Hot working operations on 80-20 brass are successful only with careful control. In this connection, lead should be kept to a trace.

Physical Properties

Melting range	960-1000°C. (1760-1832°F.)
Density	8.67 gm/cm ³
Coefficient of thermal expansion (0-100°C.)	18×10^{-6} per °C.
Thermal conductivity	0.34 cal/cm ² /cm/sec/°C.
Electrical resistivity	5.3 microns/cm ²
Electrical conductivity	32.5% I.A.C.S. at 20°C.
Modulus of elasticity, psi.	1.5×10^7
Endurance limit, psi. (rotating beam machine. Determined on basis of 100 million cycles)	20,000-25,000

The 20,000 psi. endurance limit refers to soft 80-20 brass secured by annealing at 1100°F. for 30 min. The 25,000 psi. refers to hard 80-20 brass secured by rolling to No. 4 B. & S. gage.

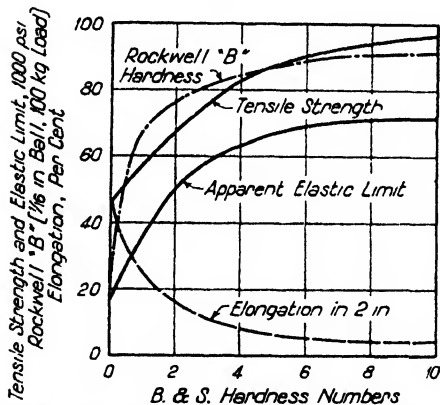


Fig. 1—Variations in properties of annealed sheet of 80-20 brass by cold rolling to 0.042 in. thick.

Fig. 1 shows the changes in mechanical properties obtained on sheet annealed to an average grain of 0.020 mm. diameter by cold rolling over a range of 11-67% reduction in area (1-10 B. & S. gage numbers).

Whereas Fig. 1 illustrates the effects on mechanical properties of cold working of annealed material, Fig. 2 traces the effects of annealing following cold working. Annealed sheet, in Fig. 1, was cold rolled four B. & S. gage numbers (35.7% reduction in area) to a final thickness of 0.042 in., and annealed for one hour at temperature, over a range of 400-1300°F. at 100°F. intervals.

Fig. 3 shows the effect of the same annealing schedule as in Fig. 2 on tubing, extruded and cold drawn to $\frac{1}{8}$ in. outside dia. by .040 in. wall thickness. The physical properties for any annealing temperature vary from those in Fig. 2, principally because of differences in degree of cold working prior to annealing. Grain size prior to cold working is also a factor.

Mechanical Properties at Elevated Temperatures—W. B. Price¹ gives results of short time tensile at elevated temperatures on 30% cold drawn 80-20 brass. The tensile strength decreases almost linearly from a room temperature value of about 80,000 psi. to less than 10,000 psi. at 900°F. Elongation is at a minimum of zero at 480°F. as compared with a room temperature value of 13%. Beyond 480°F., the elongation steadily increases to the limit of the testing temperatures (1650°F.). At 1650°F. the elongation is 27%.

D. Bunting² shows by means of Izod impact tests the existence of a brittle range in annealed 80-20 brass between 800 and 1150°F. The testing range was from room temperature to 1300°F.

Uses—Some applications for 80-20 brass are: Forming operations not requiring the superior mechanical properties of an alloy in the 70-30 range of analysis; ornamental and architectural work, and hardware; applications involving some

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corrosive conditions, as water pipe, and condenser tubing operating under certain corrosive conditions. As regards corrosion resistance, 80-20 brass is probably slightly less resistant to season cracking and dezincification than 85-15.

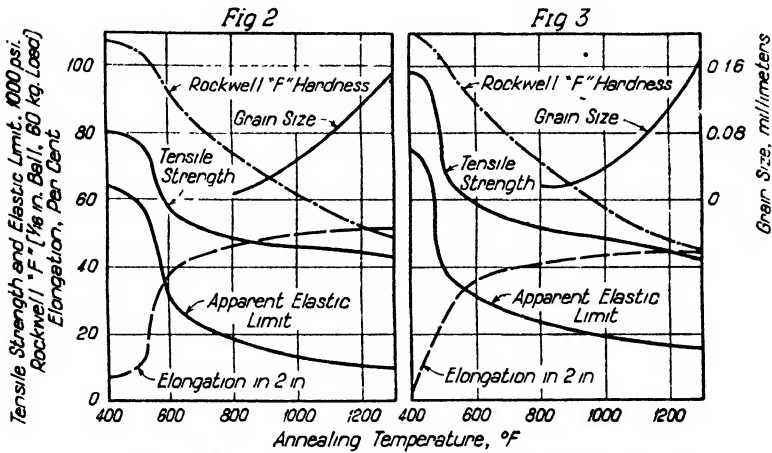


Fig. 2—Effects of annealing following cold working of 80-20 brass sheet cold rolled from four B. & S. gage No. to 0.042 in. thick then; annealed one hour at temperatures shown.

Fig. 3—Effects of annealing following cold working of 80-20 brass tubing. Extruded and cold drawn to $\frac{1}{16}$ in. outside dia. by 0.040 in. wall thickness, then annealed one hour at temperatures shown.

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Properties of Wrought Copper-Aluminum Alloys

(Aluminum Bronze)

By Jerome Strauss* and Lewis H. Fawcett†

General—The practically important wrought aluminum bronzes, or aluminum-copper alloys rich in copper, generally contain from 4-10.5% aluminum with or without other metals. When the aluminum content exceeds 11% the alloy has a marked tendency to become brittle especially when appreciable amounts of other alloying metals are present. Iron is the additional element most usually employed. Nickel and manganese with or without iron are likewise used. The compositions in frequent use for wrought aluminum bronze are more numerous than in the case of cast aluminum bronze.

These alloys combine the strength and ductility of medium carbon steel with a high resistance to corrosion when subjected to the atmosphere, salt water, sulphuric acid, and other chemicals. They may be readily forged, hot rolled, or cold rolled and some of them are susceptible to heat treatment. Aluminum bronzes possess greater resistance to corrosion than manganese bronze, they have good bearing qualities, hardness, and resistance to shock and fatigue. These properties have caused wrought aluminum bronzes to be used for diaphragms and gears and in such applications as, rods and bars requiring great strength and resistance to corrosion, valve stems, propeller blade bolts, air pumps, condenser bolts, and for purposes requiring great strength combined with good bearing qualities, such as slide liners. Sheets and strips have been made into a large variety of products by cupping, spinning most frequent use in this country (others are listed in Table I):

Composition and Manufacture—The following compositions are the alloys in most frequent use in this country (others are listed in Table I):

Type	Copper	Aluminum	Per Cent			Specification	S.A.E. Grade No.	Use
			Iron, Max.	Other Additions Including Ni, Sn and Mn, Max.	Impurities Including Zn, Cd, and Pb, Max.			
88-9-3	84-93	7-10	4.00	2.00	0.25	{Federal QQ-B-666 {Navy 46B17	B ...	Rods, bars, shapes, forgings, and general use.
95-5	92-96	4-7	0.50	....	0.50	{Federal QQ-B-666 {Navy 46B17	A 701	Plates, sheets, and strips

Type 88-9-3 is used generally for all products excepting plates, sheets, and strips, in which case Type 95-5 is employed. Melting may be accomplished by any of the usual furnaces used in making high grade copper-base alloys using good melting practice. These alloys have high liquid shrinkage and it is good practice in teeming to use large end up ingot molds with hot tops similar to the practice used in manufacturing high grade alloy steels. Aluminum bronze has a great tendency to form dross and a large amount of this dross is found on the exterior of ingots made of this alloy. The dross may be removed by machining the entire surface of the ingot excepting the hot top and bottom. An optimum forging temperature range is 1700-1450°F. and reduction in forging should not be too rapid.

Types 88-9-3 and 95-5 do not require heat treatment. Aluminum bronzes are generally not heat treated unless their aluminum content is as high as 10%. The heat treatment generally consists of quenching in water from 1500-1600°F. depending on the cross section, followed by tempering between 700 and 1100°F. in accordance with the composition and section of each individual part. Cooling in air from the quenching temperature without tempering likewise is frequently done.

Aluminum bronzes are difficult to machine but with the use of high speed steel tools with lower rake angles than for steel they are machined in regular production without serious difficulty.

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Table I
Special Aluminum Bronze Alloys
High in Strength or Ductility

Composition, %				Condition	Elastic Limit, psi.	Prop. Limit, psi.	Proof Stress, psi.	Yield Point, psi.	Tensile Strength, psi.	Elong., % in. 2 in.	Impact, Red. of Area %	Hardness	
Cu	Al	Fe	Mn									Brinell 500 kg.	Rockwell scope
92.00	7.00	1.00	....	4 in. annealed sheet, cold rolled to 2 in.	....	92,900	....	....	128,100	7.50	34.80	....	....
92.00	7.00	1.00	....	4 in. annealed sheet, cold rolled to 2 in., annealed 1300°F.	....	39,800	....	....	81,200	45.30	61.80	....	....
88.49	10.32	3.19	....	1 in. dia. forged, 1650°F. water, 1000°F. air	....	49,700	....	....	102,900	12.70	17.20	....	....
83.00	5.36	3.06	8.58	1/2 in. sq. forged, 1600°F. (30) water, 1100°F. (60) air	47,300	47,300	51,300	65,200	99,450	27.40	29.40	21.5	200.7
81.10	9.78	3.74	5.38	1/2 in. sq. forged, 1550°F. (30) air	50,950	50,950	55,250	61,650	104,800	17.30	17.80	18.2	246.0
83.27	8.64	3.11	....	7/8 in. sq. forged, 1550°F. (30) water, 200°F. (60) air	33,150	33,150	37,450	48,850	101,150	24.50	32.00	28.5	225.0
78.66	8.17	3.39	....	1/2 in. sq. forged, 1500°F. (30) air	35,700	35,700	37,950	45,050	100,200	26.20	33.40	36.8	209.0
78.66	8.17	3.39	....	1/2 in. sq. forged, 1500°F. (30) water, 1500°F. (30) air	58,550	53,450	61,850	67,500	118,800	6.30	11.50	12.6	280.5
87.45	5.62	....	6.93	1/2 in. dia. hot rolled, 1/2 in. dia. cold rolled, 575°F. (30) air	67,200	....	....	103,300	109,900	20.00	47.00	....	....
87.45	5.62	....	6.93	1/2 in. dia. cold rolled, 575°F. (30) air	76,200	....	....	116,800	117,600	12.00	43.00	....	....
87.45	5.62	....	6.93	1650°F. water, 1300°F. (30) air	9,000	....	....	19,300	65,400	73.00	69.00	....	....
87.45	5.62	....	6.93	1650°F. water, 1300°F. (30) air	29,100	....	....	50,800	96,800	26.00	25.00	....	....
84.50	6.36	....	9.14	1/2 in. sq. forged, 1600°F. (30) water, 800°F. (60) air	49,650	54,750	59,200	73,050	105,450	20.80	32.80	12.1	213.5
92.00	7.00	....	1.00	4 in. annealed sheet, cold rolled to 2 in., annealed 500°F.	....	97,800	....	....	124,000	4.50	21.60	....	....
92.00	7.00	....	1.00	4 in. annealed sheet, cold rolled to 2 in., annealed 1200°F.	....	19,200	....	....	66,200	62.30	51.60	....	....
92.00	7.00	....	1.00	4 in. annealed sheet, cold rolled to 2 in., annealed 600°F.	....	84,100	....	....	112,500	8.50	46.80	....	....
92.00	7.00	....	1.00	4 in. annealed sheet, cold rolled to 2 in., annealed 1200°F.	....	17,400	....	....	66,400	60.80	57.40	....	....
88.11	8.91	....	2.98	1 1/2 in. hot rolled, 1/2 in. sq. forged, 1550°F. (30) air	....	....	....	44,800	89,600	39.00	43.60	....	....
82.90	7.15	....	8.12	1/2 in. sq. forged, 1550°F. (30) air	49,650	48,400	52,350	60,100	94,450	28.00	39.30	31.8	207.9
82.90	7.15	....	8.12	1/2 in. sq. forged, 1550°F. (30) air	49,650	48,400	52,350	60,100	94,450	28.00	39.30	31.8	207.9

Mechanical Properties—Specimens should be of the usual form: 0.375 in. radius, 0.505 in. dia. by 2 in. gage length. The mechanical properties are as follows:

Mechanical Properties

	As Forged or Rolled	
	88-9-3	95-5
Tensile strength, psi.....	70,000-85,000	50,000-65,000
Proportional limit, psi.....	20,000-35,000	.....
Yield point, psi.....	30,000-45,000	.....
Elongation, % in 2 in.....	20-40	15-40
Reduction of area, %	20-40	15-40
Bend test	120°-180°	120°-180°
Resistance to impact (Izod), ft-lb.....	30-35	.....
Brinell hardness number (500 kg. load).....	120-135	60-120

Especially high strength or high ductility not exhibited by the standard alloys outlined above may be secured with other aluminum bronzes, if desired for special purposes, by a judicious use of the proper proportion of aluminum along with one or more of the added elements—iron, nickel, and manganese. As in steel the presence of aluminum and nickel together give opportunity for precipitation hardening; the use of these alloys has, however, been slight. The composition, treatment, and mechanical properties of some of these alloys are given in Table I.

Corrosion—The wrought aluminum bronzes like cast aluminum bronzes are suitable for types of service such as exposure to industrial atmospheres, sea air, sea water, and a large number of neutral and acid salts in low concentration at both room and slightly elevated temperatures. In heat treated parts (9.5-10.5% Al) maximum resistance to mineral acids and their salts appears to be developed by tempering (after water quenching) at 900-950°F.

Specifications—Specifications covering wrought aluminum bronze in general use are as follows:

Society of Automotive Engineers Specification, No. 701; Federal Specification, QQ-B-666; and U. S. Navy Department Specification, 46B17.

The Society of Automotive Engineers specification covers in one grade the same composition that the Federal specification classifies by the two grades A and B. The U. S. Army use Federal specification, QQ-B-666.

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Properties of Beryllium-Copper

By H. C. Jennison* and H. F. Silliman†

Alloys of beryllium and copper have been on the market in the United States since 1931. The important characteristic is the combination of high strength and hardness, high fatigue resistance, and high wear resistance in alloys which have the corrosion resistance of copper.

Composition—Beryllium-copper alloys containing up to approximately 2.75% beryllium can be produced in the form of sheet, rod, wire, and tube. With beryllium between 1.0 and 2.75% the alloy responds to a precipitation hardening heat treatment. Most of the wrought beryllium-copper available at the present time has the composition: Beryllium 2-2.25%, nickel 0.50% max., iron 0.25% max., copper balance. In tubes, the proportion of beryllium is lowered to facilitate drawing operations. The nickel content is added by one producer to refine the grain and increase the ductility.

Physical Properties—Table I gives the physical properties of beryllium-copper alloy.

Table I
Physical Properties of Beryllium-Copper Alloy
(Beryllium 2.00-2.25%)

Melting range.....	{Solidus 864°C. Liquidus 955°C.
Crystal structure, alpha phase.....	Face centered cubic
Lattice constant, alpha phase	3.56 Å
Crystal structure, gamma phase.....	Body centered cubic
Lattice constant, gamma phase	2.70 Å
Specific gravity.....	8.23 ± .02
Density	0.297 ± 0.01 lb./cu. in.
Maximum increase in density on heat treatment..	0.6%
Maximum decrease in length on heat treatment...	0.2%
Specific heat (30-100°C.).....	0.10 cal./g./°C.
Thermal conductivity (soft annealed).....	{0.16 B.t.u./sq. ft./in./sec./°F. at 68°F. 0.20 cal./cm. ² /cm./sec./°C. at 20°C.
Thermal conductivity (soft annealed, then heat treated)...	{0.20 B.t.u./sq. ft./in./sec./°F. at 68°F. 0.25 cal./cm. ² /cm./sec./°C. at 20°C.
Thermal conductivity (hard drawn).....	{0.14 B.t.u./sq. ft./in./sec./°F. at 68°F. 0.18 cal./cm. ² /cm./sec./°C. at 20°C.
Thermal conductivity (hard drawn, then heat treated)...	{0.16 B.t.u./sq. ft./in./sec./°F. at 68°F. 0.20 cal./cm. ² /cm./sec./°C. at 20°C.
Thermal coefficient of expansion (-50 to +50°C.).....	17 × 10 ⁻⁶ /°C.
Electrical resistivity at 20°C. (soft or hard drawn).....	60 ± ohms per mil ft.
Electrical resistivity at 20°C. (heat treated).....	41-59 ohms per mil ft.
Electrical conductivity at 20°C. (soft or hard drawn).....	17% ± I.A.C.S.
Electrical conductivity at 20°C. (heat treated).....	18-25% I.A.C.S.
Electrolytic potential	Negative to Hydrogen and slightly positive to Copper

Workability—Beryllium-copper may be cold worked by any of the processes which are applied to phosphor bronze in similar forms. It work hardens more rapidly than most wrought copper alloys so that annealing is required more frequently. Hot working by forging, extruding, and the like is possible but not so easy as with silicon-copper alloys, or aluminum bronze. Beryllium-copper can be soft soldered, silver soldered, and welded with the carbon arc. It can be plated with other metals by the usual methods. The alloy hardened by cold work, heat treatment, or both, is softened by heating to 775-800°C. (1427-1472°F.) and quenching rapidly in cold water. It may be hardened again by cold working and by reheating at a temperature in the range 250-325°C. (482-617°F.).

Beryllium-copper sheet, rod, wire and tubes, formed into various articles by cold working, do not require a solution heat treatment before hardening. Articles which have been formed by hot working, or articles which have been welded or hard soldered must be heated for 2 to 3 hours at 775-800°C. (1427-1472°F.) and quenched in water before they will respond satisfactorily to the precipitation hardening treatment.

The temper selected for any given article is governed by the amount of forming necessary. Sheet 0.050 in. and thinner in the soft, ¼ hard and ½ hard conditions can be bent back sharply upon itself when the bend is at 90° to the direction of rolling. For a similar bend parallel to the direction of rolling, only soft or ¼ hard strip should be used. For operations which draw the sheet, as in forming corrugated

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diaphragms, the soft or $\frac{1}{4}$ hard temper is satisfactory. Any of the tempers mentioned above may be machined with ordinary cutting tools. In general it is best to select the hardest temper which will not fail in forming.

Tensile and Hardness Properties—Beryllium-copper may be heat treated to develop values of tensile and hardness exceeding those of the hardest wrought bronzes. The hardening is accomplished by heating the alloy for a definite period

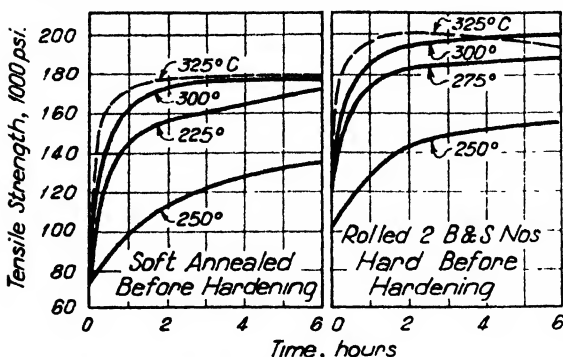


Fig. 1—Strength of Precipitation Hardened Beryllium-Copper Alloy.

of time at a carefully controlled temperature in a muffle furnace, salt bath, or oil bath. Fig. 1 shows the time and temperature relationships for commercial heat treatments. In Table II are given some average tensile properties, and Table III shows the corresponding hardness values.

Fatigue Resistance—The 2.00-2.25% beryllium-copper alloy has a higher fatigue resistance than any other wrought copper-base alloy. Endurance limits of 45,000 psi. have been reported. Lower values are obtained occasionally, so it is considered safer to base designs on an endurance

limit of 35,000 psi. In comparable tests no reduction of the fatigue resistance was noted when the specimens were kept moistened with water.

Wear Resistance—Beryllium-copper has a better wear resistance than phosphor bronze when run against all grades of steel, especially under light loading and with no lubrication. It does not compare favorably in this respect with nitrided steels.

Applications—Beryllium-copper is used in the electrical and aircraft industries, and in other fields for parts such as springs, gears, diaphragms, bearings, and other articles where the electrical conductivity, corrosion resistance, nonmagnetic properties, machinability, and ductility are required.

Table II
Average Tensile Properties of Beryllium-Copper Sheet, 0.050 in. Gage
(Beryllium 2.00-2.25%)

Condition	Proportional Limit, psi.	Yield Point 0.75%, psi.	Johnson's Elastic Limit, psi.	Tensile Strength, psi.	Elong. % in 2"	Young's Modulus, psi. $\times 10^{-6}$
Soft annealed.....	8,000	31,000	25,000	70,000	45.0	18.0
Soft, average heat treatment....	46,000	134,000	120,000	175,000	6.3	18.9
$\frac{1}{4}$ Hard.....	33,000	90,000	68,000	103,000	8.0	17.5
$\frac{1}{2}$ Hard, average heat treatment	48,000	132,000	125,000	173,000	4.8	18.5
Hard	39,000	105,000	78,000	118,000	4.3	17.2
Hard, maximum heat treatment..	55,000	138,000	146,000	193,000	2.0	18.4

Table III
Hardness of Beryllium-Copper Sheet, 0.050" Gage
(Beryllium 2.00-2.25%)

Condition	Scale B 1/16" ball 100 kg. load	Rockwell		Scale C 150 kg. load	Brinell 10 mm. ball 3000 kg. load
		Scale G 1/16" ball 150 kg. load	Scale A Brake 60 kg. load		
Soft annealed.....	65-73	31.	43.	..	110
Soft, average heat treatment.....	112.5*	102.	71.	38.	340
$\frac{1}{4}$ Hard.....	99.	79.	60.	18.	200
$\frac{1}{2}$ Hard, average heat treatment.....	112.5*	102.	71.	38.	340
Hard	102.	84.	63.	24.	220
Hard, maximum heat treatment.....	114. *	104.5	72.	41.	365

*Readings over 100 are for purpose of comparison only.

Copper-Nickel Alloys

By E. M. Wise*

Copper and nickel form a continuous series of solid solutions free from phase changes. The melting temperature rises steadily with the nickel content. (The diagram¹ is shown on page 1353. The mechanical properties reach a maximum at about 65% nickel while the electrical resistivity attains a maximum at 55% nickel, as shown in Fig. 1. Both nickel and copper possess relatively high temperature coefficients of electrical resistivity but the temperature coefficient drops rapidly toward the middle of the series and is substantially zero in the 45% nickel-copper alloy known as Constantan.^{2, 3} The thermal emf. against copper also reaches a high value near the middle of the series, the maximum occurring at about 45% nickel.^{3, 10}

Nickel is magnetic at room temperature but loses its magnetism at about 360°C. The addition of copper to nickel depresses the temperature at which the magnetic change occurs, the 67% nickel 33% copper alloy becoming nonmagnetic at about 0°C.^{3, 4}

The addition of nickel to copper rapidly effaces the red color of copper, the 15% alloy having a faint pink cast while alloys containing 20% or more nickel are essentially white.

Copper-nickel alloys containing about 2% nickel have been found useful for mechanical purposes and are employed in England for fire boxes and the like, while the ductile 15 and 20% nickel-copper alloys have been employed for bullet jackets in small arms. A far more important application of the 20% nickel alloy was found in its use for condenser tubes, which was developed independently in this country and England. This was followed by the use of the superior 30% nickel-copper alloys which have proved outstanding in condensers for marine use and for salt water piping aboard ship. Large amounts of the latter alloy are also used for condensers in oil refineries. It is notably free from pitting tendencies and due to the fact that it does not support marine growths is "nonfouling". See Reference 5 for current observations on this and other condenser tube materials and the article on page 1415 dealing with this alloy.

The 25% nickel-copper alloy is familiar to all as it is the material used for the United States "nickel" coin.

The alloy containing 45% nickel, best known as Constantan, has a temperature coefficient of electrical resistivity which is practically zero, coupled with an electrical resistivity close to the maximum of the series. These characteristics make it broadly useful for a wide variety of electrical resistors in both wrought and cast form. The high thermoelectric force of Constantan against copper, iron and chromium-nickel and the reproducibility of the alloy make it popular for thermocouples for use at low and intermediate temperatures where high sensitivity is required. A number of other copper-nickel alloys containing from ½-65% nickel are employed for electrical purposes. The ½% alloy is used in conjunction with copper for extension leads for platinum rhodium-platinum thermocouples, while alloys containing 2½-22% nickel are employed for resistors where a moderate resistivity and an intermediate temperature coefficient are desired. The 65% alloy is used where a high resistivity and a fairly low temperature coefficient of resistivity coupled with higher resistance to oxidation are required.

The addition of a small amount of nickel to copper appears to have little effect on the rate of oxidation at temperatures ranging from 800-1000°C., but as the nickel content is increased beyond 30% a marked improvement occurs and the oxidation

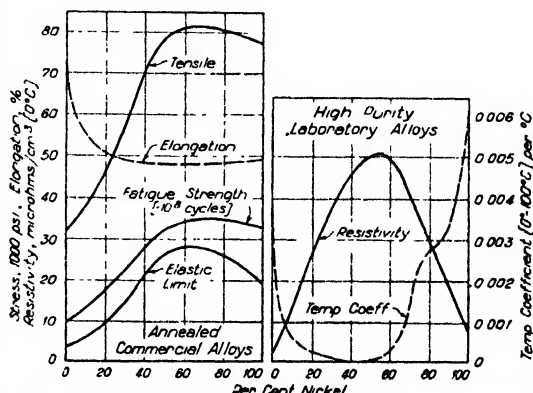


Fig. 1—Mechanical and electrical properties of annealed copper-nickel alloys.^{3, 8}

*Assistant Manager, Research Laboratory, The International Nickel Co., Inc., Bayonne, N. J.

rate below 1000°C. falls rapidly to 70% nickel and then more slowly as pure nickel is approached. Reference 7 should be consulted for more detailed discussion. The effect of temperature upon the mechanical properties of copper-nickel alloys is considered in Reference 8.

The resistance of copper, nickel and copper-nickel alloys to a wide variety of corrosives is summarized in Reference 9.

The 65% nickel alloy known as Monel possesses the highest mechanical properties of the series, good fabricating characteristics plus excellent resistance to a wide range of corrosives. For these reasons, this alloy finds broad use in the process industries and for structures where mechanical strength and resistance to corrosion are required. It also finds use where good mechanical properties, plus high impact strength are required at very low (liquid air) temperatures, as well as in steam at 800°F. For full discussion, see page 1655 devoted to this alloy.

Regular wrought Monel is generally magnetic at room temperature but becomes nonmagnetic when warmed slightly. A similar behavior is shown by the 30% nickel-iron alloys and is employed in compensating for temperature errors in magnetic speedometers and electrical measuring instruments. By adding small quantities of silicon or aluminum to Monel the temperature of the magnetic change is depressed; as a result, cast Monel, which contains appreciable silicon, may be nonmagnetic at room temperature, and "K" Monel, which contains aluminum, remains nonmagnetic at sub-atmospheric temperatures.

Alloys containing nickel contents intermediate between Monel and nickel find little use although in England application has been made of the 90% nickel 10% copper alloy to the plates of radio diodes.

Effect of Impurities—Sulphur should be kept low in all of the alloys and should be under 0.02% and preferably under 0.01%. Carbon must be held to low levels in the wrought copper-rich alloys due to its tendency to precipitate as graphite under certain annealing conditions and this precipitate considerably reduces the normal high ductility of the alloy. In the wrought 20% nickel alloy carbon in excess of 0.04% or 0.05% may cause trouble, although with ½-1% manganese it is helpful in reducing this tendency to precipitate graphite. Larger amounts of carbon are permissible in castings and in alloys of higher nickel content, a carbon content of 0.20% being quite useful in cast 65% nickel (Monel).

Manganese is useful to control the effect of sulphur in low nickel alloys, but 0.1% of magnesium, actually introduced into the melt, is required with the nickel-rich alloys. About 1% of zinc, where permissible, is helpful in deoxidizing low nickel castings which are to be rolled. 0.5% silicon plus 1% manganese is effective in sand cast 30% nickel-copper while about 1.25% silicon and about 1% manganese plus a final addition of 0.1% magnesium is suitable for sand cast 65% nickel-copper alloy. For further details the sections of the Handbook dealing with specific alloys should be consulted.

Lead in the presence of the usual amounts of silicon is highly detrimental and is apt to cause cracking and very coarse structures in sand cast material and is detrimental to the high temperature properties, hence care should be taken to completely exclude lead from these alloys.

Annealing—For annealing, nonoxidizing sulphur-free atmospheres are desirable. The annealing temperature will vary with the alloy. Temperatures of 1200°F. are employed for the 20-25% nickel alloys and up to about 1600°F. for the high nickel alloys. More information for annealing specific alloys is given in other sections of the Handbook dealing with nickel-copper alloys.

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Properties of Copper-Nickel Alloys

(Cupro-Nickel)

By H. C. Jennison* and W. S. Girvin†

The term "cupro-nickel" is a generic term applying to alloys composed entirely of copper and nickel (Cu and Ni are soluble in each other in all proportions). The principal cupro-nickel alloys at present contain nickel in the following percentages: 2½, 5, 10, 15, 20, 25, and 30.

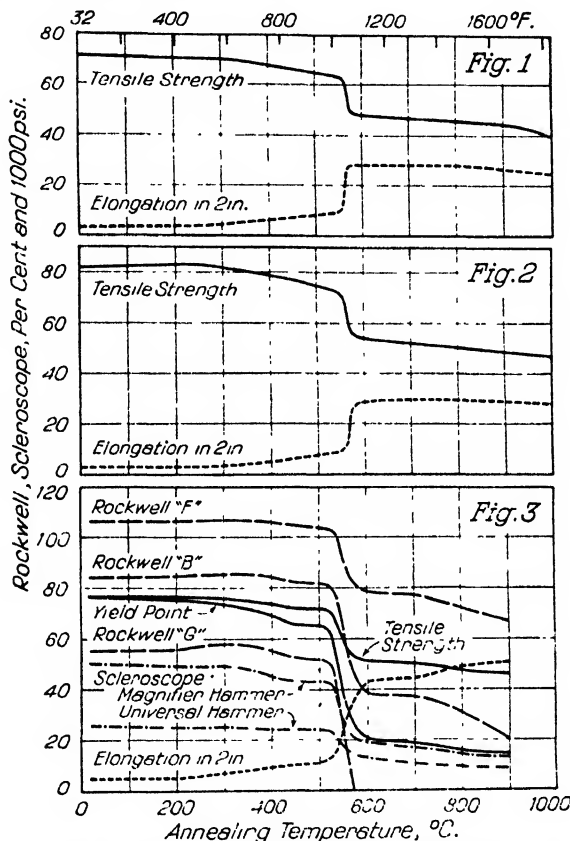


Fig. 1—Annealing 15% cupro-nickel. Rolled to 0.04 in. thick and 5 B & S No. hard. Annealed ½ hr. at temperatures noted and quenched in water. Fig. 2—Annealing 20% cupro-nickel—same conditions as for Fig. 1. Fig. 3—Annealing 30% cupro-nickel.

The alloys with 15, 20, and 30% nickel are the most common. They have the following characteristics:

Nickel, %	Melting Point ¹ , °C.	Density, lb. per cu.in.	Electrical Conductivity, % I.A.C.S. at 20°C.	Temp. Coefficient of Electrical Resistance at 20°C.	Thermal ² Conductivity cal./sq.cm./cm./sec./°C. at 20°C.	Thermal ² Conductivity K. at 200°C.	Temp. Coefficient of Thermal Conductivity at 20°C.
15	1175	0.323	8.78	0.000344	0.112	0.144	0.00161
20	1200	0.323	6.474	0.000237	0.087	0.112	0.00163
30	1225	0.323	4.75	0.000048	0.069	0.088	0.00156

*Deceased. †Asst. Metallurgist, The American Brass Co., Waterbury, Conn.
 This article was not revised for this edition.

The 30% cupro-nickel is extensively used for condenser tube purposes and for handling salt water aboard ships and containers for handling corrosive substances in many branches of the chemical industry; also used for resistance wire. It can

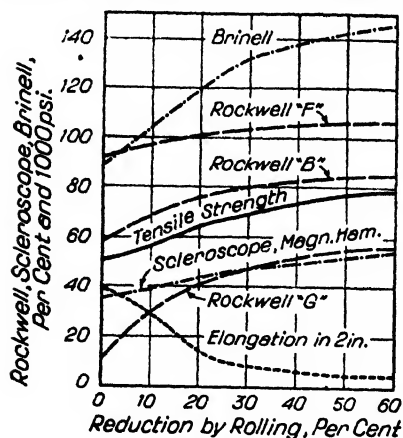


Fig. 4—Rolling 30% cupro-nickel.

be hot forged, cold rolled or drawn and withstands severe bending operations. It is readily soft soldered, silver soldered, brazed, arc and gas welded. The melting point of 30% cupro-nickel welding rod is 1225°C. (2237°F.).

The 20% cupro-nickel is used for turbine blades and parts where resistance to corrosion and erosion is required.

Cupro-nickel being essentially a copper-base alloy has the fundamental corrosion-resistance associated with copper increased by the corrosion-resistance inherent to nickel. Cupro-nickel, like copper, is resistant to corrosion by all types of atmospheres, natural and industrial waters and sea water as well as many of the mineral and organic acids. Because of the high nickel content the alloys show superior resistance to alkalis. As the nickel content is increased to 30%, the corrosion resistance is improved.

Average Physical Properties of 20% Cupro-Nickel at Elevated Temperatures

Temp., °C.	Tensile Strength, psi.	Elongation in 2 in., %
22	64,560	15.5
70	60,820	15.5
120	60,010	12.5
170	56,730	11.5
220	55,790	12.0
270	52,810	11.0
320	50,910	10.5

References

- ¹W. Guertler and G. Tammann, *Über Kupfernickellegierungen*, Z. anorg. Chem., 1907, v. 52, p. 27.
- ²C. S. Smith and E. W. Palmer, *Thermal and Electrical Conductivities of Copper Alloys*, A.I.M.E. Technical Publication, No. 648, 1935.

Properties of the Alloy 55% Copper-45% Nickel (Constantan)

By G. C. Stauffer*

General—The 55% copper-45% nickel alloy has about the highest electrical resistivity, the lowest temperature coefficient of resistance, and the highest thermal emf. against platinum of any alloys of these metals. Because of these properties it is used in electrical resistors and thermocouples.

General Properties—The properties of this alloy are as follows:

Melting Point, °C.....	1210 (2210°F.)		
Density, g. per cm. ³	8.9 (0.322 lb./in. ³)		
	20-100°	20-500°	20-1000°C.
Linear Coefficient of Expansion, per °C.....	14.9 × 10 ⁻⁶	16.3 × 10 ⁻⁶	18.8 × 10 ⁻⁶
Thermal Conductivity, cal./cm./sec./C.*.....	0.0546		
Specific heat, cal./g.....	0.094		
Electrical Resistivity, microhm-cm.....	49		
	20-100°	20-250°	20-500°C.
Temperature Coefficient of Resistance ..	±00002	0	±000025
Thermal, emf. vs. platinum, 0°-1000°C. millivolts.....	43.92		
Tensile Strength, annealed, psi.....	60,000		
Tensile Strength, cold worked, psi.....	135,000		
Maximum temperature of use, for resistors, °C.....	500		
Maximum temperature of use, for thermocouples, °C...	900		

Thermal Emf.—The basic alloy is modified by additions of manganese and iron to give somewhat varied emf. as specified by pyrometer manufacturers. Representative values obtained by the United States Bureau of Standards are given in Table I. These values establish the shape of the temperature emf. curve.

Table I*
Emf. vs. Platinum Cold Junction at 32°F.

°F.	Millivolts	°F.	Millivolts
-300	+ 5.02	800	-17.41
-200	+ 3.73	900	-19.97
-100	+ 2.24	1000	-22.55
0	+ .57	1100	-25.15
100	- 1.27	1200	-27.77
200	- 3.26	1300	-30.39
300	- 5.39	1400	-32.99
400	- 7.64	1500	-35.58
500	- 9.98	1600	-38.14
600	-12.40	1700	-40.66
700	-14.88	1800	-43.13

*From Research Paper No. 1080, National Bureau of Standards, Washington, D. C.

Temperature Coefficient of Resistance—The change in resistance with temperature may be either positive or negative, depending on small variations in composition and on variations in the amount of cold working. In any case, the change is very small. Average values are given under General Properties for various temperature ranges.

*Driver-Harris Co., Harrison, N. J.

Properties of Cast Copper 45% Nickel Alloy*

By W. A. Graham*

The binary copper-nickel alloy containing 54-56% copper and 44-46% nickel is characterized by high electrical resistance and low temperature coefficient of resistance. The alloy is generally used in the wrought condition, but may be cast with satisfaction, yielding the following properties in the cast condition:

Ultimate tensile strength, psi. (Min. to average ¹).....	54,000-56,000
Yield strength, psi. (Average ²).....	21,000
Elongation, % in 2 in. (Average).....	32
Reduction of area, %.....	34
Brinell hardness, 10 mm. ball—500 kg. load.....	75-85
Rockwell hardness, $\frac{1}{16}$ ball—100 kg. load.....	B48-B54
Shearing strength, psi. (Approx.).....	43,000
Charpy impact resistance, ft.-lb. (Approx. ³).....	29.5
Specific gravity (Approx.).....	8.6
Weight per cu. in., lb. (Approx.).....	.309
Pattern maker's shrinkage, in. per ft.....	$\frac{1}{4}$
Solidification range, °C.....	1225-1275
Specific resistance, ohms per cir. mil. ft.....	294
Specific resistance, ohms per sq. mil. ft.....	231
Temperature coefficient of resistance, 0°-150°C. per °C.....	± 0.0001

¹Tension values determined from standard 0.505 test specimens cast in green sand molds.
²Yield strength defined as the stress at which the stress-strain curve shows a departure of 0.2% from the modulus line produced.
³Charpy impact values determined using 10 x 10 mm. specimens on standard Charpy machine.

General Properties and Uses—Pure copper and nickel are melted together usually in an arc furnace. The pouring temperature required is 1350°C., minimum. The melt is deoxidized just before pouring with a suitable deoxidizer such as magnesium. When pouring each mold, the gate should be kept full until the mold is filled. The rate of filling the mold should be controlled by the size of the runner and not by varying the rate of pouring.

Due to its electrical properties the alloy is primarily for use in grid resistors. It is customary to match high and low resistance grids so that the total variation per set is held to a minimum.

*Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

*Constantan.

Properties of Cast Copper-30% Nickel Alloy (Cupro Nickel)

T. E. Kihlgren*

Properties of castings containing 70% copper and 30% nickel are given in Table I.

Table I¹
Tensile Properties of Cast 30% Cupro Nickel
(30% Ni, 0.50% Si, 1% Mn, 1% Fe, balance Cu)

Ultimate tensile strength, psi.....	63,000-68,000
Yield point (.5% extension under load), psi.....	32,000-35,000
Yield strength (2% offset), psi.....	30,000-34,000
Proportional limit, psi.....	18,000-22,000
Elongation, % in 2 in.....	35-40
Reduction of area, %.....	45-50
Brinell hardness number, 1000 kg.....	115-125

¹Tensile properties based on bars cast from 150 lb. oil fired crucible and 250 lb. rocking type electric furnace heats from electrolytic copper, electro-nickel, refined silicon, and low carbon manganese metal.

Specifications

Source	Designation
U. S. Navy, Bureau of Engineering (tentative).....	SPS 171

Effect of Various Elements on Tensile and Casting Properties—When small amounts of carbon, aluminum, and titanium are present, the general level of strength properties is raised, and in some cases the ductility is decreased. Silicon has a vigorous effect on the physical properties, and an increase in silicon in the above mixture to 0.75% results in a tensile strength of approximately 75,000-85,000 psi. and a yield point of 55,000-60,000 psi. and a Brinell hardness number of about 170. The ductility is reduced sharply with increased silicon and is of the order of 12-20% at the 0.75% silicon level. In general, it is preferable to keep silicon nearer 0.5% as the higher silicon alloys are somewhat sensitive to hot cracking. Iron, up to 1.50% increases the yield point and proportional limit quite sharply, and the tensile strength moderately, without loss of ductility but excessive amounts are undoubtedly detrimental from a corrosion standpoint. Manganese has a rather mild effect on the tensile strength but is decidedly helpful from a casting angle, as its presence with silicon improves the fluidity of the alloy. It also materially improves the resistance of the casting to hot cracking when subjected to stress while cooling in the mold.

Lead is extremely deleterious in the silicon containing cupro-nickel, giving rise to excessive hot cracking, rendering the alloy useless. It should be virtually excluded from the mixture.

Uses—The alloy is used for cast fittings such as couplings, tees, ells, pump and valve bodies, and employed in conjunction with the wrought 70:30 copper-nickel alloy, which finds use in marine salt water lines, condensers in marine and seaboard applications and in oil refineries.

Cupro nickel castings (30% nickel) of various types may also be used under service conditions where physical properties and corrosion resistance intermediate between those of nickel-silver and various high nickel content alloys are appropriate.

Foundry Practice—A method for the production of pressure tight castings in this alloy has been recently described by the author.¹

References

- ¹T. E. Kihlgren, Production of Pressure Tight Castings in 30% Cupro Nickel, Trans., A.F.A., 1937, v. 45, p. 225.

*Metallurgist, Research Laboratory, The International Nickel Co., Inc., Bayonne, N. J.

Properties of Copper-Silicon Alloys*

General—The cast and wrought copper-silicon alloys usually contain one or more other elements and are of commercial importance because they resist the action of many corroding agents and have the strength of mild steel. They can be cast, rolled, spun, stamped, forged, and pressed either hot or cold and can be readily welded by all the usual methods. They are supplied in the form of sheets, strip, plates, wire, rods, tubes, pipe, casting ingots, hot pressed parts and special shapes.

Composition and Physical Constants—The trade name, manufacturer, nominal composition, physical constants, and A.S.T.M. specification number and type are given in Table III.

Mechanical Properties—Mechanical properties of sheets, strip, plates, rods, bars, shapes and wire are given in Tables I, II, IV, and V, which are taken from various A.S.T.M. specifications listed in Table III.

Table I
Copper-Silicon Alloy Plates and Sheets for Unfired Pressure Vessels
A.S.T.M. Designation B96-36T

Temper	Tensile Strength, psi.	Yield Strength ^a , psi.	Elongation, % in 2 in.	Rockwell F Scale ½ in. Ball 60 kg. Load	Hardness ^b B Scale ½ in. Ball 100 kg. Load	Grain Size ^b Maximum, m/m
			Types A and C			
Hot rolled.....	55,000	20,000	50	F72	.....	....
Hot rolled with cold rolled finish.....	58-72,000	23,000	20	.....	B60-B80	.....
Annealed.....	50-64,000	18,000	40	F72-F92	.....	0 110 ^c
Half hard.....	71-81,000	40,000	10	.....	B79-B91	.....

Minimum values except as noted.

^aStress corresponding to 0.5% strain. ^bHardness and grain size values are given for informative purposes only. ^cNo minimum grain requirement is specified, but all annealed material shall be fully recrystallized.

Table II
Copper-Silicon Alloy Sheet and Strip
A.S.T.M. Designation B97-36T

Temper	Tensile Strength, psi.	Rockwell Hardness ^a		Grain Size ^a m/m
		F Scale ½ in. Ball 60 kg. Load	B Scale ½ in. Ball 100 kg. Load	
		Types A and C Alloy		
0.070 m/m Anneal.....	52,000- 58,000	F76-F80	.....	0 050-0.110
0.040 m/m Anneal.....	55,000- 64,000	F76-F93	.....	0 055(max) ^b
Quarter hard.....	62,000- 72,000	.....	B65-B80	.....
Half hard.....	71,000- 81,000	.....	B79-B91	.....
Hard.....	87,000- 97,000	.....	B88-B96	.....
Extra hard.....	99,000-108,000	.....	B93-B98	.....
Spring.....	105,000-113,000	.....	B94-B99	.....
		Type B Alloy		
0.070 m/m Anneal.....	38,000- 45,000	F45-F55	.....	0 050-0.120
0.070 m/m Anneal.....	40,000- 50,000	F50-F75	.....	0 060(max) ^b
Quarter hard.....	42,000- 52,000	.....	B48-B63	.....
Half hard.....	47,000- 57,000	.....	B64-B73	.....
Hard.....	60,000- 70,000	.....	B74-B82	.....
Extra hard.....	67,000- 76,000	.....	B78-B85	.....
Spring.....	71,000- 79,000	.....	B81-B86	.....

^aGrain size and Rockwell hardness values are for informative purposes only. ^bNo minimum grain size requirement is specified but all annealed material shall be fully recrystallized.

Uses—Bolts, screws, nails, rivets, range boilers, tanks, small arms ammunition, electrical apparatus, sewage disposal apparatus, ventilators, ducts, fans, skylights, containers for handling gases, levee revetment work, transmission and distribution line hardware and fittings, signal apparatus, electrical conduit, bearing plates, chemical process machinery, flagpoles, Fourdrinier wire and cloth, kick plates, laundry

*Prepared by a Subcommittee consisting of W. R. Hibbard, Chairman; W. B. Price, D. E. Crampton, R. A. Wilkins, R. S. Pratt, and H. A. Staples.

Table III.—Trade Name, Nominal Composition, and Physical Constants of Copper-Silicon Alloys

Table III.—Trade Name, Roman Numeral, Composition, and Specifications of Various Alloys													
Trade Name	Duronze I ^a Duronze II ^a Olympic A ^b Olympic B ^b Olympic C ^b Olympic D ^b Olympic W ^b Cusilloy ^c PMG3 ^d PMG10 ^d PMG94 ^d PMG95 ^d PMG96 ^d												
Nominal Composition, %:													
Copper	97.50	97.12	96.0	97.5	94.75	95.5	97.0	95.0	98.2	95.6	93.0	96.6	97.0
Silicon	0.90	2.88	3.0	1.5	4.25	3.0	3.0	3.0	1.2	3.2	2.5	2.5	2.5
Lead						0.5						0.4	
Zinc			1.0	1.0	1.00	1.0					4.0		
Iron								1.0	0.6	1.2	0.5	0.5	0.5
Tin								1.0					
Physical Constants:													
Melting point °C.	1040	1025	1027	1060	8.37	1027	1027		1060	1020		1025	1030
Specific gravity	8.785	8.55	8.58	8.73	8.32	8.58	8.58		8.78	8.55		8.66	8.63
Weight per cubic inch, lb.	.3172	.309	.310	.316	.302	.310	.310		.317	.309		.313	.312
Electrical conductivity, I.A.C.S. at 20°C., %	13	6.5	7.5	12.0		8.6	8.6		15	6.5	8	8	8.0
Coefficient of linear expansion °F.	.0000093	.0000093	.0000096	.0000093		.0000096	.0000096			.0000096			.0000096
Thermal conductivity (approx. % Copper), %	20	9	8.6	14		7.5	7.5		21	7.5	9.0		9.0
Young's modulus of elasticity	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000
A.S.T.M. Specifications													
Type:													
B96-36T		A.C.	A.C.					A.C.		A.C.	C		C
B97-36T		A.C.	A.C.	B				A.C.	B	A.C.	C		C
B98-36T		A.C.	A.C.	B				A.C.	B	A.C.	C		C
B99-36T		A.C.	A.C.	B				A.C.	B	A.C.	C		C
Trade Name ^a	Everdur 1010 ^a	Everdur 1015 ^a	Everdur 1012 ^a	Everdur 1000 ^a	Everdur 418 ^t	Herculoy 419 ^t	Herculoy 420 ^t	Herculoy 421 ^t					
Nominal Composition, %:													
Copper	95.8	98.25	95.75	95.0	96.4	97.63	95.9	98.00					
Silicon	3.1	1.50	3.00	4.0	3.1	2.12	3.1	1.75					
Lead		0.25	1.00	1.0			1.0	0.25					
Manganese	1.1												
Zinc													
Iron													
Tin													
Aluminum													
Physical Constants:													
Melting point °C.	1019	1055	1019	1000	993	1021	1019	1055					
Specific gravity	8.539	8.740	8.539	8.15	8.54	8.54	8.54	8.74					
Weight per cubic inch, lb.	.308	.316	.308	.294	0.308	0.313	0.308	0.316					
Electrical conductivity, I.A.C.S. at 20°C., %	6.0	8.5	6.2	5.6	8.1	10.9	6.7	12.0					
Coefficient of linear expansion °F.	.0000096	.0000093	.0000096	.0000096	.0000096	.0000096	.0000096	.0000096					
Thermal conductivity (approx. % Copper), %	8.4	14.0	8.4	7.2	9.3	10.6	8.4						
Young's modulus of elasticity	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000	15,000,000					
Trade Name ^a	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.	Chase Brass & Copper Co.					
Trade Name ^a	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.	Bridgeport Brass Co.					
Trade Name ^a	Copper Inc.	Copper Inc.	Copper Inc.	Copper Inc.	Copper Inc.	Copper Inc.	Copper Inc.	Copper Inc.					

^aSee last page of this article for A.S.T.M. specifications and types covering these alloys.

Table IV
Copper-Silicon Alloy Rods, Bars and Shapes
A.S.T.M. Designation B98-36T

Temper	Diameter or Distance between Parallel Faces	Tensile Strength psi. Min.	Yield Point ^a psi. Min.	Elonga- tion in 2 in., % Min.	Bend Test Angle of Bend Degrees
Types A, C and D Alloy					
Soft	All forms, all sizes	52,000	.....	45	180
Quarter hard..	All forms, all sizes	55,000	24,000	30	120
Half hard, Rods	Up to ½ in. incl.	70,000	38,000	20	120
	Over ½ to 1 in. incl.	70,000	38,000	25	120
	Over 1 to 2 in. incl.	70,000	38,000	30	120
	Bars and Shapes	_b	_b	_b	_b
Hard, Rods.....	Up to ½ in. incl.	85,000	50,000	14	90
	Over ½ to 1 in. incl.	85,000	50,000	18	90
	Over 1 to 1½ in. incl.	85,000	50,000	22	90
	Bars and Shapes	_b	_b	_b	_b
Extra hard ^c , Rods...	Up to ½ in. incl.	100,000	55,000	7	60
	Over ½ to 1 in. incl.	100,000	55,000	10	60
	Over 1 to 1½ in. incl.	100,000	55,000	14	60
Type B Alloy					
Soft	All forms, all sizes	40,000	.....	35	180
Half hard, Rods.....	Up to ½ in. incl.	55,000	20,000	11	180
	Over ½ to 1 in. incl.	55,000	20,000	14	180
	Over 1 to 2 in. incl.	55,000	20,000	17	180
	Bars and Shapes	_b	_b	_b	_b
Hard, Rods.	Up to ½ in. incl.	65,000	35,000	6	120
	Over ½ to 1 in. incl.	65,000	35,000	8	120
	Over 1 to 2 in. incl.	65,000	35,000	10	120
	Bars and Shapes	_b	_b	_b	_b
Extra hard ^c , Rods...	Up to ½ in. incl.	75,000	40,000	4	90
	Over ½ to 1 in. incl.	75,000	40,000	6	90
	Over 1 to 1½ in. incl.	75,000	40,000	8	90

^aStress corresponding to 0.5% strain. ^bPhysical requirements of bars and shapes of the half hard and hard tempers are agreed upon between the manufacturer and the purchaser at the time of order. ^cBars and shapes are not produced in extra hard temper.

equipment, heat exchanger tube and head plates, structural shapes, welding rod, electric refrigerators, air conditioning apparatus, propeller shafts, tiller rope, marine hardware, meters, carburetor and valve parts, pump rods.

Castings—With correct foundry practice, standard tension test specimens, poured from copper-silicon alloy ingots in sand molds, and tested without machining, gave the following properties: Tensile strength, 40,000-53,000 psi.; elongation in 2 in., 25-50%.

Corrosion Resistance—These alloys, like copper, are satisfactory in contact with a number of corrosive solutions and compounds. This corrosion resistance may be adversely affected by the presence of oxidizing agents.

The alloys are employed in engineering construction because of their high strength combined with the fundamental corrosion resistance of copper and may be used in practically all locations where copper is satisfactory, but where greater strength than copper is desired.

The metal has been found of value for resistance to atmospheric corrosion in both industrial and marine locations and resistant to corrosion by sea water as well as corrosive industrial and natural waters, to sulphuric and hydrochloric acid and many of their salts, to alkalis and many of the alkali salts. It shows good resistance to certain organic compounds including alcohol, phenol, cresol, sugar solutions, fatty acids, and organic salts.

These alloys are under the Boiler Code Rules and are acceptable at a 10,000 psi. working stress for all temperatures from room temperature up to 250°F. Above 250°F. and up to a maximum of 350°F., these alloys are allowed a maximum working stress of 5,000 psi. The question of doubt in regard to contact with steam and

Table V—Copper-Silicon Alloy Wire for General Purposes

A.S.T.M. Designation B99-36T

Temper	Physical Properties	Up to ¼ in. incl. in Diameter	Over ¼ in. in Diameter
Types A, C and D Alloy Wire			
Annealed.....	Grain Size, max., m/m	0.040 ^a	0.040 ^a
	Tensile Strength, psi.	55,000-70,000	55,000-65,000
	Elongation ^b in 2 in., min. %	40	47
Eighth hard.	Elongation ^b in 10 in., min. %	30	e
	Tensile Strength, psi.	62,000-78,000	62,000-78,000
	Elongation ^b in 2 in., min. %	20	28
Quarter hard	Elongation ^b in 10 in., min. %	7	e
	Tensile Strength, psi.	72,000-85,000	72,000-85,000
	Elongation ^b in 2 in., min. %	15	18
Half hard...	Elongation ^b in 10 in., min. %	5	e
	Tensile Strength, psi., min.	90,000	90,000
	Elongation ^b in 2 in., min. %	4	10
Hard.....	Elongation ^b in 10 in., min. %	1.5	e
	Tensile Strength, psi., min.	115,000	115,000
	Elongation ^b in 2 in., %	2	6
Spring ^d	Elongation ^b in 10 in., %	0.75	e
	Tensile Strength, psi., min.	135,000	130,000
	Elongation ^b in 2 in., %, min.	1.5	4
	Elongation ^b in 10 in., %, min.	0.5	e
Type B Alloy Wire			
Annealed.....	Grain Size, max., m/m	0.040 ^a	0.040 ^a
	Tensile Strength, psi.	43,000-50,000	43,000-50,000
	Elongation ^b in 2 in., %, min.	33	40
Eighth hard..	Elongation ^b in 10 in., %, min.	25	e
	Tensile Strength, psi.	50,000-60,000	50,000-60,000
	Elongation ^b in 2 in., %, min.	12	20
Quarter hard'	Elongation ^b in 10 in., %, min.	4	e
	Tensile Strength, psi.	60,000-75,000	60,000-75,000
	Elongation ^b in 2 in., %, min.	8	15
Half hard....	Elongation ^b in 10 in., %, min.	2.5	e
	Tensile Strength, psi., min.	75,000	75,000
	Elongation ^b in 2 in., %, min.	4	10
Hard.....	Elongation ^b in 10 in., %, min.	1	e
	Tensile Strength, psi., min.	90,000	90,000
	Elongation ^b in 2 in., %, min.	3	8
Spring ^d	Elongation ^b in 10 in., %, min.	0.75	e
	Tensile Strength, psi., min.	100,000	100,000
	Elongation ^b in 2 in., %, min.	2	6
	Elongation ^b in 10 in., %, min.	0.50	e

^aNo minimum grain size requirement is specified but all annealed material shall be fully recrystallized. ^bElongation may be determined in either the 2 in. or 10 in. gage length but not in both in any instance. ^cOn wire ¼ in. in diameter, the percentage of elongation shall be taken in 2 in. ^dThe term "Spring Temper" does not necessarily indicate a reduction of 8 B&S gage numbers on these alloy wires as in the case of brass.

steam mixtures is covered by a warning which appears in a footnote to the table of allowable working stresses on nonferrous materials which reads as follows:

There is doubt concerning the suitability of this material when exposed to certain products and/or high temperatures, particularly steam above 212°F., and the user should satisfy himself that it is satisfactory for the service for which it is to be used.

Workability—The copper-silicon alloys listed in Table III can be hot worked at 1100-1475°F., except Type D containing lead to make them free-machining. All alloys except Olympic C and Everdur 1000 can be cold worked commercially. They can be readily drawn, rolled, spun and stamped. The Type B alloys can be easily cold forged.

Welding Properties—Copper-silicon alloy can be satisfactorily welded by the oxy-acetylene, metallic arc, and resistance methods. For details of welding see page 220.

Annealing—Copper-silicon alloys Types A, B and D will recrystallize after severe cold reduction at approximately 750°F. and at somewhat higher temperatures following more moderate reductions. The annealing range suggested is from 900°F. for light anneals to 1300°F. for full anneals, depending somewhat on the size or thickness and the degree of softness desired. The oxide formed during annealing is particularly tenacious and the usual brass mill pickle solution containing 10-20% sulphuric acid leaves copper-silicon alloys with a thin oxide coating of dark red color. This red oxide surface is highly satisfactory for many uses. Except

where a bright surface is wanted for its color or for welding, this pickled finish is suggested as being satisfactory and less expensive.

The pickled copper-silicon alloy can be brightened by dipping in a solution composed of 15% sulphuric acid and $\frac{1}{4}$ lb. per gallon of sodium bichromate. The temperature of the solution should be held at approximately 100°F. After the metal is taken from this solution it should be thoroughly rinsed in cold water and then dipped for a few seconds in a solution composed of 15% sulphuric acid and 2% hydrofluoric. It should then be removed and given a thorough rinsing in cold water to remove any white deposit still clinging to the metal. If it is necessary to prevent water stains, the metal can be dipped in hot water and then dried on a hot sawdust bench. The usual precautions should be taken with the sulphuric-hydrofluoric dip to prevent fumes from injuring the work.

A.S.T.M. Specifications and Types

(For Everdur and Herculoy as listed in Table III)

A.S.T.M. Specification Type	Everdur 1010	Everdur 1015	Everdur 1012	Everdur 1000	Herculoy 418	Herculoy 419	Herculoy 420	Herculoy 421
B96-36T	A,C	..	..	..	A,C	..	A,C	.
B97-36T	A,C	B	..	..	A,C	B	A,C	B
B98-36T	A,C	B	D	..	A,C	B	A,C	B
B99-36T	A,C	B	D	..	A,C	B	A,C	B

Properties of Cast Copper-Aluminum Alloys

(Aluminum Bronze)

By Jerome Strauss* and Lewis H. Fawcett†

General—Aluminum bronzes comprise a group of copper-base alloys containing from a small amount up to 16% of aluminum (more generally 5-11% aluminum) with or without appreciable additions of other metals. These additions are principally iron, nickel, and manganese; tin and zinc are occasionally used. The compositions in general use for sand or chill castings are less numerous than those used in the case of wrought material.

This group of alloys has high strength combined with ductility, low coefficient of friction against steel and some other metals, hardness comparable to manganese bronze and resistance to corrosion, to shock, and to fatigue. On account of these properties aluminum bronze has been applied in gun mounts, gears of various types for heavy machinery and light automotive construction, feed nuts, bearings, propellers, pump parts, fans, and ornamental work.

Composition and Application—Typical compositions used in the United States are as follows:

Type	Copper, %	Aluminum, %	Iron, %	Tin, %, Max.	Total Other Elements, %, Max.	Specifications
88-9-3	87.0-89.0	7.0-9.0	2.5-4.0	0.50	1.0	A.S.T.M.-B59-36
89-10-1	89.5-90.5	9.5-10.5	1.0 max.	0.20	0.50	A.S.T.M.-B59-36
90-9-1	88.0-92.0	7.0-9.0	1.25 max.	0.50	1.0	.....
90-10	88.0-91.0	9.5-10.5	0.20	0.50	1.0	.....

Type 88-9-3 is used generally, 89-10-1 where high tensile strength after heat treatment is required, while 90-9-1 is frequently used on castings of small cross sectional area (under $\frac{1}{2}$ in.). As type 90-10 contains no iron its yield point is apt to be low especially when slowly cooled after casting; this restricts its use somewhat, but for certain types of wearing qualities where neither high hardness nor ductility is required, this alloy is sometimes preferred.

Manufacture—Aluminum bronzes are difficult to cast due to high liquid shrinkage and a tendency to form dross, but these characteristics may be overcome by simple design, dry sand molds, the use of chills and good general foundry practice; as part of the last item, it is especially important to avoid turbulent flow of the metal into the mold. These alloys are not materially affected by the usual contaminating metals in small amounts but if consistently high physical properties are desired the use of commercially pure metals in preparing the alloys is recommended. Nickel or manganese as a major constituent increases the ductility over that found in the binary combinations, but they contribute less to elastic strength and hardness than does iron.

Aluminum bronze may be melted in the usual types of brass and bronze melting furnaces. The optimum pouring temperature may be as low as 1950°F. for heavy castings or as high as 2150°F. for light castings or those chilled over a large portion of their surface.

The 89-10-1 composition may have its strength increased by heat treatment;

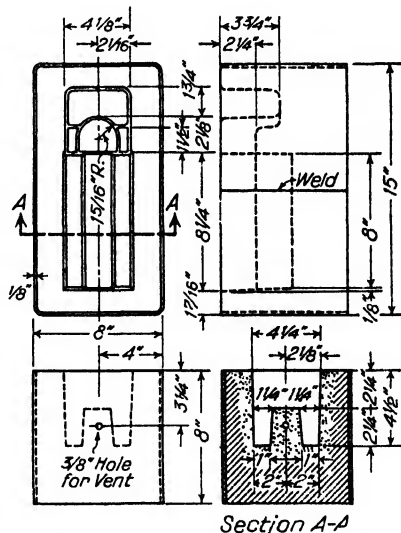


Fig. 1—Test coupon and cast bar.

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that is, usually quenching in water from 1500-1600°F., depending on the thickness and actual aluminum content, followed by tempering between 700°F. and 1100°F. in accordance with the section of each individual part.

Mechanical Properties—Test coupon and separately cast bar of the types usually used for these high shrinkage alloys are shown in Fig. 1. The specimen machined from these cast blocks should be of the usual form: 0.375 in. radius, 0.505 in. dia. by 2 in. gage length. The mechanical properties are given below:

Mechanical Properties

88-9-3, As Cast

Tensile strength, psi.....	65,000-75,000
Proportional limit, psi.....	20,000-25,000
Yield point, psi*.....	25,000-30,000
Elongation, % in 2 in.....	20-40
Reduction of area, %.....	20-35
Resistance to impact (Izod), ft-lb.....	20-30
Brinell hardness number (500 kg. load).....	90-110

Alloy 89-10-1, Heat Treated

Tensile strength, psi.....	80,000-90,000
Proportional limit, psi.....	30,000-40,000
Yield point, psi*.....	50,000-60,000
Elongation, % in 2 in.....	5-10
Reduction of area, %.....	8-12
Brinell hardness number (3,000 kg. load).....	170-200
Compression of 0.001 in., psi.....	54,000
Compression of 0.05 in., psi.....	100,000

Alloy 90-9-1, As Cast

Tensile strength, psi.....	60,000-70,000
Proportional limit, psi.....	15,000-20,000
Yield point, psi*.....	20,000-25,000
Elongation, % in 2 in.....	20-40
Reduction of area, %.....	20-35
Resistance to impact (Izod), ft-lb.....	20-30
Brinell hardness number (500 kg. load).....	70-100

Alloy 90-10, As Cast

Ultimate tensile strength, psi.....	60,000-75,000
Proportional limit, psi.....	10,000-11,000
Yield point, psi*.....	20,000-25,000
Elongation, % in 2 in.....	15-25
Reduction of area, %.....	15-25
Resistance to impact (Izod), ft-lb.....	20-30
Brinell hardness number (500 kg. load).....	90-100
Compression of 0.001 in., psi.....	16,000-19,000
Compression of 0.1 in., psi.....	75,000-83,000
Compression of 0.13-0.16 in., psi.....	100,000
Patternmaker's shrinkage, in. per ft.....	7
Sp.gr. (approx.).....	7.5
Weight per cu.in., lb. (approx.).....	0.27
Relative electrical conductivity (Cu = 100).....	12.5
Modulus of elasticity, psi.....	12,000,000-15,000,000

*0.5% permanent set.

Corrosion—The uses of the cast aluminum bronzes have been briefly noted earlier in this article. It need merely be stated here, therefore, that the types of service for which these alloys are suited include also exposure to industrial atmospheres, sea air, sea water, and a large number of neutral and acid salts in low concentration at both room and slightly elevated temperatures.

Specifications—Specifications in general use covering aluminum bronze castings are as follows: A.S.T.M., B59-36; S.A.E. No. 68; Federal Specification, QQ-B-671, and U. S. Navy Department Specification, 46B18.

The S.A.E. specification conforms to the A.S.T.M. specification B59-36 and the Navy Department specification conforms in technical details to Grade A of the Federal specification. The U. S. Army uses Federal specification QQ-B-671.

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Properties of Cast Copper-Lead-Tin Alloy

(Cu 80%, Pb 10%, Sn 10%)

By Dr. G. H. Clamer*

The alloy known as 80-10-10 is a copper base alloy composed of 80% copper, and 10% each of tin and lead, and may contain from traces up to 1% of phosphorus. When the phosphorus content approaches 1%, it is known as 80-10-10 phosphor bronze.

The alloy is primarily a bearing metal and was developed to replace the so-called copper-tin bronzes formerly used for such purposes. The addition of lead resulted in greatly improving the antifrictional qualities of the alloy. It also had the effect of facilitating machining, and improving casting properties. As a result this alloy has widespread acceptance as a standard bearing metal.

It is estimated that in excess of 10,000,000 lb. of this alloy are cast annually in the United States.

Structure—Microstructurally, this alloy consists of a matrix of copper and tin, containing a small amount of lead in solution, the balance of the lead being mechanically held. The constitutional diagram of the matrix is shown in Fig. 1, page 1365.

Composition—Although there are a number of specifications covering this alloy, the one most widely used is that of the A.S.T.M., B30-36, Alloy No. 16.

Specification B30-36

	Desired, %	Min., %	Max., %
Copper	80	79	..
Lead	10	9	11
Tin	10	9	11
Zinc .....	..	..	0.50
Phosphorus .....	..	0.05	..
Antimony .....	..	..	0.50
Nickel .....	..	..	0.25
Iron .....	..	..	0.25
Sulphur .....	..	..	0.08
Aluminum .....	..	..	None
Silicon .....	..	..	0.03
Other than copper, lead, tin, zinc, nickel, and antimony.....	..	..	0.50

Effects of Major Constituents—Increase of tin increases the hardness and compressive strength of the alloy and also increases the rate of wear. Increase of lead promotes plasticity of the alloy, gradually decreases strength, improves machinability, and lowers elongation. Phosphorus when added in small amounts acts as a deoxidizer and when present in appreciable quantities increases hardness, tensile strength, and fluidity of the alloy, and lowers its melting point.

Impurities—**Zinc**—Zinc within limits of specification has no detrimental effect on this alloy when phosphorus is present in amounts not exceeding 0.05%. However, when an appreciable amount of phosphorus is present, it increases grain size and lowers the physical properties of the alloy. It also has a tendency to increase the rate of wear and to cause lead segregation.

Antimony—Antimony increases the grain size and lowers the physical properties of the alloy.

Iron—Iron is an impurity in the alloy. It is found in solution or in the free state. In both cases it is detrimental and should be kept as low as possible. When in the free state it makes hard spots, and when in solution it increases internal shrinkage and discolors the alloy.

Nickel—Nickel is not an objectionable impurity but is sometimes added for its ability to hold the lead and to increase the density of the alloy, which naturally increases its other physical properties.

Sulphur—Sulphur is an impurity in this alloy. There is some question as to the amount necessary to produce distinctly harmful results. Recommended prac-

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tice relative to this impurity awaits results from work now in progress. Up to 0.08% is not considered harmful.

Aluminum—Aluminum is an extremely dangerous impurity and even a few hundredths of a per cent is likely to ruin the alloy, making it unsound. Aluminum apparently alters the crystalline structure of the alloy markedly, even small amounts cause lead sweats.

Silicon—Silicon has somewhat the same effect as aluminum on this alloy. It causes excessive dross formations and general unsoundness, and imparts a white discoloration on the surface of the castings. It also has the effect of producing lead sweats.

Physical Properties for Sand Castings

Ultimate tensile strength, psi.....	28,000-35,000
Proportional limit in tension, psi.....	9,500-11,500
Yield point in tension, psi.....	20,000-22,000
Elongation in 2 in., % (average).....	13
Reduction in area, % (average).....	12
Compression of 0.001 in. at.....	13,500-15,000
Compression of 0.1 in. at.....	45,000-47,000
Compression* at 100,000 lb., in.....	0.27-0.30
Brinell hardness No., 500 kg. (average).....	63
Patternmakers shrinkage, in. per ft.....	$\frac{1}{4}$
Specific gravity.....	8.9
Weight per cu. in., lb.....	0.324
Resistance to shear by impact, Izod.....	3-8
Landgraf-Turner endurance, number of alterations.....	150-500

*The compression test specimens used were cylinders 1 sq in cross sectional area and 1 in. high.

Properties of Wrought Manganese Bronzes

By H. C. Jennison* and V. P. Weaver**

The wrought manganese bronzes covered by this article are copper-zinc alloys of the Muntz metal type improved by the addition of small amounts of manganese, tin, and iron. Tin imparts appreciable hardness and strength and also noticeably improves corrosion resistance by reducing dezincification, a type of attack to which such alloys are prone. Iron also increases the hardness and strength and acts as a grain growth inhibitor. Manganese also refines the grain structure, increases strength, and improves the working properties. The following composition limits are specified in Federal Specification QQ-B-721a (Class A) and United States Navy Department Specification 46B15c covering manganese bronze bars, plates, rods and shapes: copper, 57-60%; tin, 0.5-1.5; iron, 0.8-2.0; manganese (max.), 0.50; aluminum (max.), 0.25; lead (max.), 0.20; other impurities (max.), 0.10; and zinc, remainder.

A typical nominal composition is 59% copper, 39% zinc, 0.5% manganese, 0.8% iron, and 0.7% tin.

The approximate physical properties are as follows:

Melting point, °C.....	896
Electrical conductivity, % I.A.C.S. at 20°C.....	24.6
Thermal conductivity, cal. per sq. cm. per cm. per sec. per °C. at 20°C..	0.241
Average coefficient of linear expansion per °C. from 25-300°C.....	0.000021
Specific gravity.....	8.365
Density, lb. per cu. in.....	0.302
Modulus of elasticity, in tension, psi.....	15,000,000

The usual requirements for tensile properties in accordance with the aforementioned Federal Specification (Class A) are given in Table I:

Table I
Tensile Properties of Wrought Manganese Bronze

Form, temper, and dia. or thickness, in.	Tensile Strength, psi. (min.)	Yield Strength or yield point, psi. (min.)	Elongation in 2 in. or 4 times dia. ¹ (min.), %	Bend test, degrees
Rods and bars, soft ²	Footnote 3	Footnote 3	Footnote 3	180
Rods and bars, half hard				
1 and less.....	72,000	36,000	20	120
Over 1 to 2.5, incl.....	70,000	35,000	20	120
Over 2.5.....	65,000	32,000	25	120
Rods and bars, hard:				
1 and less.....	80,000	56,000	10	90
Over 1 to 2.5, incl.....	78,000	55,000	15	90
Over 2.5.....	68,000	45,000	20	90
Shapes, soft, all sizes.....	55,000	22,000	25	180
Plates, soft:				
0.5 and less up to 30 in. wide, incl....	57,000	22,000	20	180
0.5 and less, over 30 in. wide, and all over 0.5 thick.....	56,000	22,000	25	180
Plates, half hard:				
0.5 and less, up to 30 in. wide, incl....	60,000	24,000	18	120
0.5 and less, over 30 in. wide and all over 0.5 thick.....	58,000	23,000	22	120

¹When round specimens, other than type 1 are used for testing rods, bars, and shapes, elongation shall be determined on a gage length of 4 times diameter. ²Soft rods and bars are intended for reforcing. ³No requirement.

Manganese bronze has relatively poor cold working properties but excellent hot working properties. Forging is best done in the temperature range from 650-750°C. The machinability is rated at about 30% that of free cutting yellow brass rod. The alloys are readily welded by the oxy-acetylene torch and with zinc-free copper alloy welding rods such as some of the phosphor bronzes and copper-silicon alloys, carbon arc welds of moderate strength can be obtained. Because of the high vaporization of zinc from the base metal, they are not suited to metallic arc welding but thin sheets can be resistance welded.

*Deceased. **Assistant metallurgist, The American Brass Co., Waterbury, Conn.

Manganese bronze is available in the form of bars and plates, rods, shapes, sheets, strips, wire and die pressed forgings. Material manufactured to the above mentioned specifications may be either hot or cold finished and is annealed or treated to meet the mercurous nitrate strain test. Such material is intended for purposes requiring great strength and incorrodibility such as valve stems, propeller blade bolts, air pumps, and condenser bolts and may be used in lieu of Naval brass where high strength is required.

Manganese bronze under some conditions is subject to season or corrosion cracking; it should, therefore, be manufactured to meet the strain test requirement of standard specifications and special consideration should be given to working stresses.

Manganese bronze welding rod is made to the following composition requirements of Federal Specification QQ-R-571 and Navy Specification 46R1b covering Nonferrous Welding Rods for Gas Welding: copper, 57.0-60.0%; manganese, 0.3-1.0%; iron, 0.3-1.0%; tin (max.), 1.0%; lead (max.), 0.15%; aluminum (max.), 0.15%; and zinc, remainder.

Such rods are used for general welding of brass and bronze sheets, plates, shapes and castings. Manganese bronze welding rod is also used for the oxy-acetylene welding of steel, cast iron and malleable cast iron and for building up wear resisting surfaces.

The wrought manganese bronzes belong to that group of alloys known as "high tensile strength brasses."

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The Properties of Cast Manganese Bronzes

By Lewis H. Fawcett*

Introduction—Manganese bronze is a copper-zinc alloy containing aluminum, manganese and iron; and occasionally nickel or tin. It is also (and more correctly) referred to as manganese brass, aluminum brass, complex brass, high strength brass, high tenacity brass and high tensile brass. Apparently the first public mention of manganese bronze is to be found in "The Times" (London) of February 21, 1876. This article cited the results of mechanical tests made at the Royal Arsenal, Woolwich, on certain new alloys (copper-tin-iron-manganese bronzes) introduced by P. M. Parsons. About 1888 Parsons replaced the tin in his manganese bronze by larger percentages of zinc, thus converting the alloy from one that had at least some small claim to the name bronze into a true brass, nevertheless the name bronze has persisted.

Application—Properly made manganese bronzes produce strong, ductile, non-magnetic castings possessing resistance to the corrosive action of sea water, sea air, waste water, industrial atmospheres and other corroding agents. Nevertheless, there is a probability of season cracking when manganese bronze is stressed above its yield point in certain applications such as valves. It is used for various parts of marine engine pumps, hydraulic machinery, valves, propeller hubs, propeller blades, engine framing, gears, worm wheels and general industrial purposes requiring high strength engineering castings.

Composition—The ranges of composition generally employed in this country for manganese bronze and high tensile manganese bronze are given in Table I.

Table I
Composition of Manganese Bronze

Elements	Manganese Bronze	High Tensile Manganese Bronze
Copper	55.00-60.00	64.00-71.00
Zinc	38.00-42.00	19.00-22.00
Tin	1.50, max.	0.02, max.
Manganese	3.50, max.	3.50-4.50
Aluminum	1.50, max.	4.50-6.00
Iron	0.40-2.00	2.00-3.00
Lead	0.40, max.	0.02, max.

The usual type of manganese bronze, namely, the type with higher zinc content, is approximately a 60-40 brass to which has been added small percentages of aluminum, manganese and iron, for example 58% Cu, 39% Zn, 1% Al, 1% Mn, and 1% Fe.

Manganese bronze of extremely high tensile strength may be made of a composition which is approximately: 67.50% Cu, 21% Zn, 5% Al, 4% Mn, and 2.5% Fe.

Physical and Mechanical Properties—The mechanical properties of a high-shrinkage alloy such as manganese bronze, are usually determined on a specimen cut from the test coupon of a separately cast bar such as shown in Fig. 1 in the article "Cast Aluminum Bronze." The machined specimen should be of the usual form: 0.375 in. shoulder radius, 0.505 in. dia. by 2 in. gage length. Physical and mechanical properties are given in Table II.

Manufacture—When passing from the liquid to the solid state manganese bronze has greater shrinkage than most brass or bronze alloys. It also has a strong tendency to form dross and scum. These difficulties may be overcome by care in design, the use of dry sand molds, chills, massive feeder heads, the prevention of turbulent flow of metal into mold, and good general foundry practice. Manganese bronze may be melted in the usual types of furnaces used in melting brass, bronze and other nonferrous metals and alloys.

Specifications—Specifications covering manganese bronze castings are as follows: A.S.T.M., B54-27; S.A.E. No. 43; Federal Specification QQ-B-726; and U. S. Navy Department Specification 49B3.

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Table II
Physical and Mechanical Properties of Manganese Bronze

	Manganese Bronze	High Tensile Manganese Bronze
Ultimate tensile strength, psi.....	65,000-75,000	100,000-115,000
Yield point, psi.....	25,000-40,000	55,000-75,000
Elastic limit, psi.....	15,000-25,000	50,000-55,000
Modulus of elasticity, psi.....	12,200,000	15,800,000
Elongation, % in 2 in.....	20-40	10-20
Reduction of area, %.....	20-40	10-20
Compression of 0.001 in., psi.....	20,000-26,000	60,000
Compression of 0.1 in., psi.....	85,000-90,000	90,000
Compression of 0.18 in., psi.....		100,000
Resistance to impact (Izod), ft.-lb.....	20-40	7-11
Brinell hardness number.....	109-120 (500 kg. load)	200-270 (3000 kg. load)
Specific gravity (approx.).....	8.4	7.11
Weight per cu. in., lb. (approx.).....	0.303	0.282
Weight per cu. ft., lb. (approx.).....	523	487
Patternmaker's shrinkage, in. per ft.....	7/32	7/32
Pouring temperature, °F.....	1725-1900	1800-1900
Thermal coefficient of expansion per °F.:		
from 70-200°.....	0.00001877	0.00000990
from 70-300°.....	0.00001101	0.00001018
from 70-400°.....	0.00001137	0.00001048
from 70-500°.....	0.00001177	0.00001099
from 70-600°.....	0.00001210	0.00001161
Electrical conductivity, % of copper standard (approx.)	24.2	12.8

S.A.E. No. 43 conforms with the composition and physical properties of A.S.T.M., B54-27 and Navy Department Specification 49B3 conforms in technical detail to Federal Specification QQ-B-726. The U. S. Army uses Federal Specification QQ-B-726.

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Properties of Copper-Nickel-Tin Alloy†

By W. B. Price*

This alloy contains nominally 70% copper, 29% nickel, and 1% tin. The proportion of copper and tin is the same as in regular Admiralty condenser metal, while nickel replaces a like percentage of zinc.

Physical Properties and Composition—Typical tension test values obtained on 1 in. hot rolled hexagon rod are:

Composition, %			
Cu	69.12	Elastic limit, psi.	30,500
Fe	0.18	Yield point, psi.	35,800
Sn	1.03	Tensile strength, psi.	64,500
Ni	28.23	Elongation, in 2 in. %	46
Mn	0.94	Reduction in area, %	72.2
S	0.01		
C	0.06		
Zn	0.43 (difference)		

The alloy is readily hot rolled between 2000 and 1550°F. or may be cold rolled or cold drawn. When cold drawn to wire of 0.006 in. dia. with 99.6% final reduction, the alloy has a tensile strength of approximately 131,000 psi., and an elongation of 2% in 2 in. In the annealed state this wire has a tensile strength of approximately 77,000 psi., and an elongation of about 35% in 2 in.

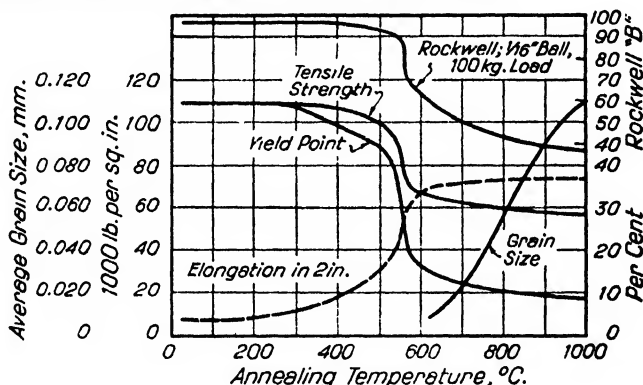


Fig. 1—Annealing test on hot worked 0.102 in. strip. Analysis: Cu 71.21%, Fe 0.35%, Sn 1.07%, Ni 26.42%, C 0.04%, Mn 0.56%, Si 0.12%, Zn (diff.) 0.23%. Material cast and hot worked to 0.599 in., then cold rolled to 0.102 in., 15 No. hard (reduced 83%) before annealing.

Fig. 1 shows the recrystallization temperature of the alloy when very hard worked to be about 1040°F. Grain growth after recrystallization is nearly in direct proportion to the annealing temperature.

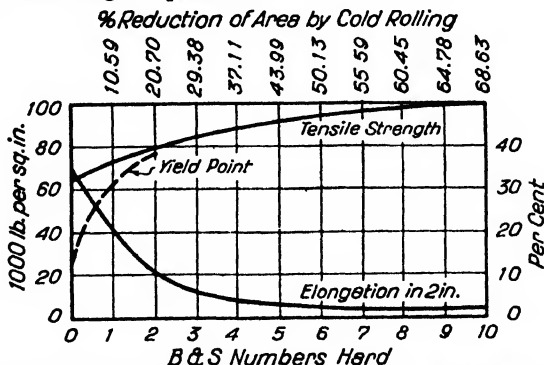


Fig. 2—Effect of cold rolling on tensile properties of strip. Anneal at 1435°F. before rolling. Gauge: Soft 0.102 in.; 10 No. hard 0.032 in. Composition same as Fig. 1.

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†The trade name of this alloy is Adnico.

Fig. 2 and 3 show the effect of cold rolling on the physical properties of strip.

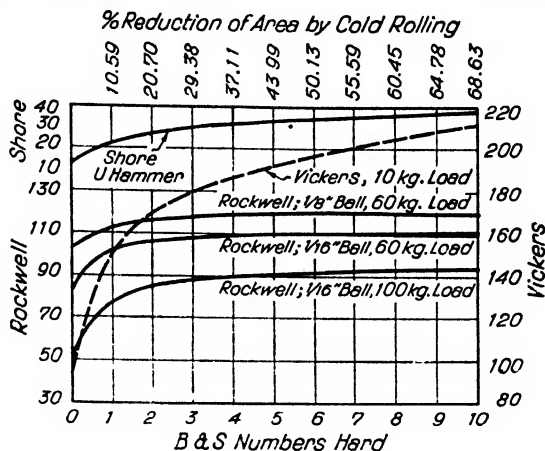


Fig. 3—Effect of cold rolling on hardness of Admic strip. Anneal at 1435°F. before rolling. Gage: Soft 0.102 in.; 10 No. hard 0.032 in.

Fig. 4 shows the improvement that may be effected in cold drawn wire by slight alteration of chemical composition. This wire contained 3% less copper, 3% more nickel and ½% more zinc. The lower Cu, higher Ni material was originally softer, hardened faster and reached a greater final strength.

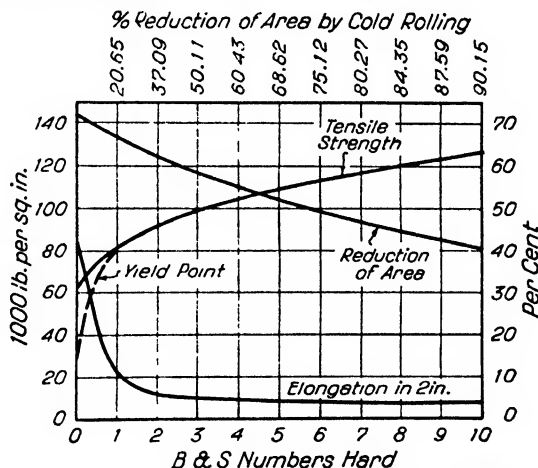


Fig. 4—Effect of cold drawing on tensile properties of wire. Analysis: Cu 68.15%, Fe 0.60%, Sn 1.11%, Ni 28.37%, C 0.04%, Mn 0.51%, Si 0.05%, Zn (diff.) 1.17%. Material cast and hot worked to ½ in. wire, then cold drawn. Gage: Soft 0.257 in. (grain size of 0.045 mm.); 10 No. hard 0.081 in.

In Fig. 5 the results of short time tension tests at elevated temperatures are given. The alloy used in these tests was annealed 1 in. rod, having a tensile

Table I
Creep Characteristics By "Up-Step" Loading

Temp., °F.	Stress for Designated Rate of Creep Rate = % per 1000 hr.		
....	0.01	0.10	1.00
600	13,800	18,900	25,500
800	4,500	7,900	14,000
1000	630	1,300	2,700

strength of 64,000 psi. The yield point and elastic limit values are abnormally high for an annealed nonferrous alloy, which is probably due to a carbon content of 0.11%, approximately twice the normal.

The results of creep tests¹ at 400, 600, 800, and 1000°F. are shown in Fig. 6 and Table I. The data were determined by the "up-step" loading method. This method consists of applying a fixed load and holding constant until creep either proceeds at

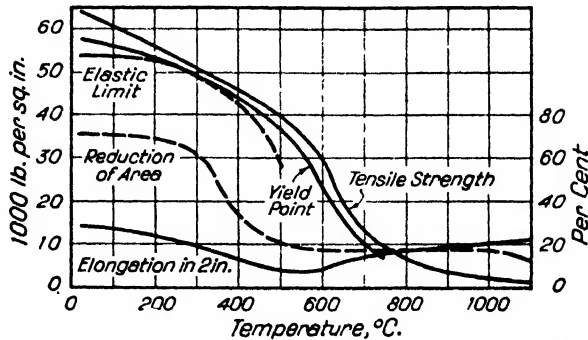


Fig. 5—Short time tensile properties of Cu, Ni, Sn alloy rod at elevated temperatures.

a constant rate for at least 200 hr. or until it comes to a complete stop for at least 200 hr. The load on the specimen is then increased and the procedure repeated.

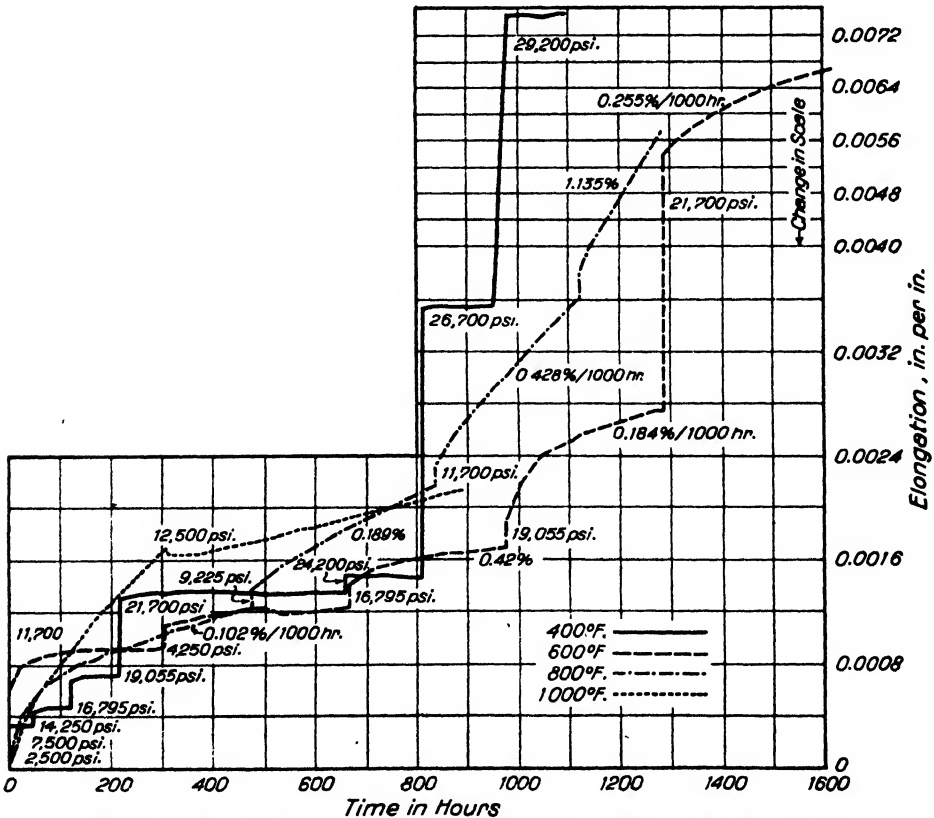


Fig. 6—Time by elongation curves of Cu, Ni, Sn alloy at 400, 600, 800, and 1000°F.

¹A. E. White, O. L. Clark, and L. Thomassen, An Apparatus for the Determination of Creep at Elevated Temperatures, Trans., Am. Soc. Mech. Eng., Fuel and Steam Power Section, v. 52, No. 27, p. 347.

The load carrying ability at 800°F. is somewhat better than that of plain carbon steel at 1000°F., since the value usually reported for a rate of flow of 0.01% per 1000 hr. for carbon steel at 1000°F. is about 3,500 lb. It is doubtful if this copper alloy can be successfully used at 1000°F. except in cases where a large amount of deformation can be allowed.

At 400°F., the elastic plus plastic deformation occurs immediately upon the application of the load, or within a relatively short time afterwards, and then creep comes to a complete stop, at least within the sensitivity of the equipment used.

Corrosion Resistance—The corrosion resistance of this alloy is an important factor in many of its applications. It is basically a copper-nickel alloy of the type that has been used extensively because of its resistance to corrosion, but its properties are enhanced by the addition of tin. For general guidance the following typical application may be noted:

Condenser Tubing	Laundry Machining
Table Ware—Restaurant Ware	Pulp and Paper Machinery
Diaphragm Metal	Plumbing Supplies

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Cast Copper-Nickel-Tin Alloys (Nickel Bronzes)

E. M. Wise*

The addition of from ¼-2% nickel to the commonly employed tin bronzes increases the strength properties, particularly the yield strength, and improves fluidity, reduces the grain size and aids in securing hydraulic tightness.^{1,2} A broad range of nickel bronzes can be further hardened and strengthened by conventional age hardening treatments analogous to those employed with duralumin and beryllium copper.^{3,4,5}

Reference to the copper-nickel-tin diagram⁶ on page 1371 will show that a considerable change in the solid solubility of a nickel content phase occurs with a

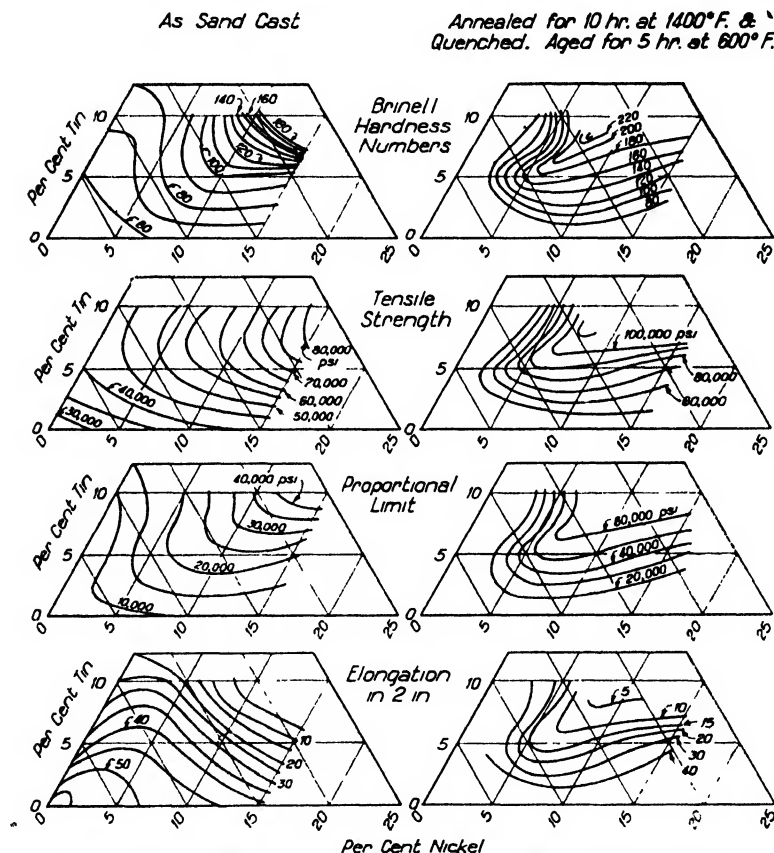


Fig. 1—Properties of nickel bronzes as cast and after heat treatment.

change in temperature and it is this characteristic which permits these alloys, over a considerable range of composition, to be softened by annealing at 1400°F. and cooling, and subsequently hardened by heating for a few hours at 550-600°F. While the highest properties are secured by the above treatment, substantial hardening can be achieved by merely aging the cast alloy for about 5 hr. at about 600°F.

The presence of lead in castings which are to be used as cast is no more detrimental to the properties than in nickel-free bronze, but lead must be excluded rigorously from castings which are to be heat treated as even traces seriously reduce the elongation and retard the age hardening reaction.

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The properties of as cast nickel bronzes and those of homogenized, quenched and aged alloys as reported by Wise and Eash¹ are shown in Fig. 1. As will be observed, the strength properties for a given copper content tend to reach their maxima when the nickel and tin contents are equal. The effect of temperature of aging upon the hardness and tensile properties of the 5% nickel 5% tin 2% zinc alloy is shown in Fig. 2.²

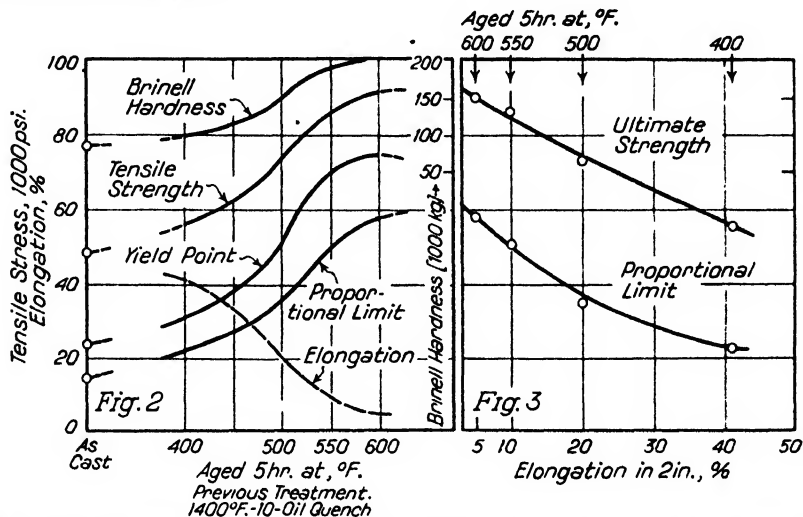


Fig. 2—Effect of aging upon the cast and heat treated 5% nickel 5% tin 2% zinc alloy.

Fig. 3—Relation between tensile strength, proportional limit, and elongation.

In common with other age hardened alloys, precipitation hardening occasions some reduction in ductility. The relation between proportional limit, tensile strength, and elongation for the cast and heat treated 5.0% nickel 5% tin alloy is shown in Fig. 3.³ Relations of this type permit a proper balance to be struck between the strength and elongation to meet particular engineering requirements.

It may be remarked that the 7.5% nickel 8% tin 2% zinc composition is rather vigorous in its response to age hardening and for general application the slightly softer 5% nickel 5% tin alloy generally provides sufficient strength and is readily handled in the foundry. It is also a good general purpose alloy for use in the as cast state without heat treatment. The melting and casting of this alloy have been studied in considerable detail by Kihlgren whose recent paper should be consulted for detailed information.⁴

The composition and properties of the sand cast 5% nickel 5% tin 2% zinc alloy are as follows: Nickel, 5-5½%; tin, 5-5½%; zinc, 1-2%; phosphorus, .03-.05%; lead, absent; iron and other impurities low, and the balance copper.

	Tensile Psi.	Yield Point, Psi. (0.5% under load)	Elongation, % in 2 in.	Brinell Hardness No., 1000 kg.
As cast	48,500	24,400	40	85
Cast and aged, 550°F. for 10 hr.	73,000	61,000	5	170
Cast and annealed, 1400°F. for 10 hr., quenched and aged, 550°F. 5 hr.	87,000	70,000	10	190
By adjusting the aging temperature, the properties can be had.....	70,000- 90,000	50,000- 70,000	25-5	140-200

Melting Practice and Heat Treatment—The melting and casting of nickel bronzes follows good bronze practice. Melting under oxidizing conditions is desirable and, in alloys to be age hardened, definite oxidation of the copper-nickel base is important. This is accomplished by melting the copper and nickel under a light charcoal cover and stirring in 0.2% of cuprous oxide when the charge has melted. The oxides

are then reduced by adding 0.03% phosphorus and the zinc and tin are introduced. A final addition of 0.05% phosphorus has been found effective with the 5% nickel 5% tin 2% zinc alloy. Other deoxidizers, such as 0.15% silicon plus 0.6% manganese or 0.05-0.1% barium have been found effective in the 7.5% nickel 8% tin 2% zinc alloy but if silicon is employed in the 5-5 alloy an increase in nickel content of about 1% must be made to secure age hardening.

As earlier mentioned, lead must be excluded from castings which are to be heat treated and for this reason good quality virgin metals and only clean revert scrap should be employed for such castings.

The annealing or homogenizing treatment is usually carried out at 1400°F., five hours at temperature being sufficient for most compositions. The rate of cooling from the homogenizing temperature can be varied within wide limits without much effect on the properties after aging, although water quenching or air cooling are usually most suitable. The time and temperature of aging are selected to give the most desirable combination of strength and elongation, 550-600°F. for 5 hr. being generally suitable for the 5% nickel 5% tin and 7.5% nickel 8% tin alloys of commercial purity. The rate of cooling from the aging temperature is unimportant.

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Properties of Copper-Nickel-Zinc Alloys

By H. C. Jennison* and W. S. Girvin†

Composition—The alloy†† has a composition of copper 75%, nickel 20%, and zinc 5%. It has a bright nickel-like appearance. Another copper-nickel-zinc alloy known as alloy 854 contains 30% nickel instead of 20% and 5% zinc. These alloys can be bent, stamped, spun, formed, drawn cold, or hot forged. Being a copper-base alloy it has the fundamental corrosion resistance associated with copper but increased by the nickel additions.

These alloys resist corrosion in all types of atmospheres; natural and industrial waters and sea water, as well as many of the mineral and organic acids. They are of

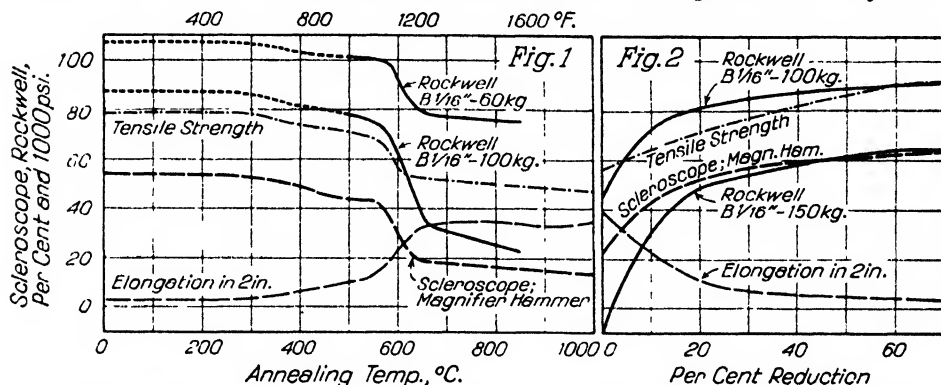


Fig. 1—Sheet of alloy 850 rolled from 5 B & S No. to 0.032 in. annealed 1/4 hr. at temperature indicated.

Fig. 2—Sheet of alloy 850, 0.145 in. gage rolled to 0.045 in.

particular value where resistance to corrosion by impingement attack is encountered, such as in condenser tubes and piping for handling salt water and alkalis.

Annealing—The annealing temperature is 1100°F. For deep drawing, an annealing temperature of 1475°F. should be used.

Physical Properties

Density at 20°C. (68°F.):

8.84 g. per cc.
0.320 lb. per cu.in.
553 lb. per cu.ft.

The density is 0.62% less than copper. If accurate weights are required multiply the values in standard copper weight tables by 0.9938.

Electrical resistivity at 20°C. 172 ohms per circular mil-ft. Circular mil-ft.—172 ohms.

Melting point—1150°C. (2102°F.).

Coefficient of thermal expansion—0.0000164°C.
0.0000091°F.

Modulus of elasticity—19,000,000 psi.

Mechanical Properties (Room Temperature)—Minimum tensile properties of this alloy in its several forms are given below and in Fig. 1 and 2.

Hard Drawn Rods

Dia., in.	Yield Point, psi.	Tensile Strength, psi.	Elongation in 2 in., %
1/8–1/4, incl.	50,000	65,000	8
Over 1/4–1/2	45,000	60,000	20
Over 1/2–3	25,000	50,000	30

Cold Rolled Plates, Sheets and Strips

Thickness and Width, in.	Yield Point, psi.	Tensile Strength, psi.	Elongation in 2 in., %
0–1/4 up to 30 wide	45,000	60,000	10
0–1/4 over 30 wide	25,000	50,000	20
Over 1/4—all widths	20,000	48,000	25

†Asst. Metallurgist, The American Brass Co., Waterbury, Conn. *Deceased.

††The trade name of this alloy is Ambrac.

Hard Drawn Tubes

Outside Dia., in.	Yield Point, psi.	Tensile Strength, psi.	Elongation in 2 in., %
½-1½	50,000	65,000	8
Over 1½	25,000	60,000	10

Wire

Temper			Elongation in 10 in., %
Spring	65,000	100,000	0.25
Medium hard.....	55,000	80,000	0.25
Annealed	25,000	50,000	20.00

Mechanical Properties (Elevated Temperatures)—Hard drawn and annealed rods tested at elevated temperatures gave the following results in short time tests:

Temp. at Which Test Was Made, °C.	Tensile Strength, psi.	Elongation in 2 in., %
<i>Hard Drawn</i>		
22	63,180	13.3
70	61,340	12.5
120	59,560	12.5
170	56,550	12.0
220	55,100	12.0
270	53,350	11.5
320	49,220	11.0
370	45,840	12.0
420	43,290	10.0
470	40,140	13.5
520	33,720	10.5
<i>Annealed</i>		
22	51,610	37.5
70	48,510	38.5
120	46,350	35.5
170	43,760	34.0
220	42,200	34.5
270	40,210	32.5
320	38,770	34.0
370	37,680	30.0
420	36,250	27.0
470	32,160	22.0
520	25,640	15.0
570	20,760	13.5

Applications—This copper-nickel-zinc alloy is being used for making screen cloth, tableware, window and door frames, tubes for oil coolers, heat exchangers, salt evaporators, and condenser tubes. The metal can be used as welding rod on a wide variety of base metals. It can be used with either the oxy-acetylene or electric methods. The alloys are available in the form of wire, rods, bars, sheets, strips, tubes, and shapes.

Castings—Casting ingots are produced in both the 20 and 30% alloys. The chemical and physical properties of the 20% alloy are as follows: Cu 64.5%, Zn 7.5%, Ni 20.0%, Pb 5.0%, and Sn 3.0%.

Physical Properties

*Tensile strength, psi.....	40,000-45,000
*Yield point, psi.....	25,000
*Elongation, % in 2 in.....	15-20
*Brinell hardness.....	55-65
Specific gravity.....	8.92
Density, lb. per cu.in.....	0.322
Melting point.....	1080°C. (1976°F.)
Pattern shrinkage.....	½ in.

*Approximate figures from tests made on sand cast bars.

The castings are used for architectural applications, general purposes, and where a corrosion resistant metal is required.

Properties of Wrought Nickel Silvers

(Copper-Nickel-Zinc Alloys)

By T. E. Kihlgren*

The nickel silvers are alloys of copper, nickel, and zinc which owe their importance to color, a degree of corrosion resistance higher than that of the common brasses, good mechanical properties, moderate cost, reasonably good productive facility, and availability in a wide variety of cast, rolled, and extruded shapes. In addition to white alloys, subdued pink, green, and yellow tints can be secured by suitable adjustment of copper, nickel, and zinc contents, and these colored alloys have useful architectural applications.

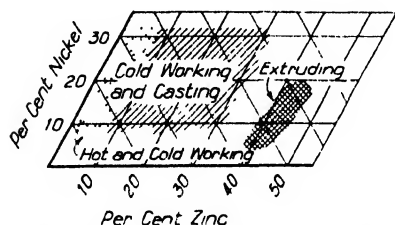


Fig. 1—Composition ranges of nickel silvers.

containing about 18% nickel, 17-20% zinc, balance copper. In some instances about 1% of lead is added to improve the machinability, particularly when the alloy is in rod form.

Where deep drawing properties are required, however, lead is undesirable, and this element is also frequently responsible for "fire cracking." The low zinc alloys may be satisfactorily worked both hot or cold. The best known of these is the 20% nickel alloy with 5% of zinc. At the 30% nickel level the 5% zinc alloy formerly produced has been largely supplanted by a simple 30% copper-nickel. A small amount of zinc is sometimes added to the latter to obtain sound sheet bars, only a trace usually remaining in the metal.

The extruding alloys are only hot worked, possessing poor cold workability, the presence of the body-centered beta phase conferring an excessively rapid rate of work hardening. The hot working properties are excellent and 8, 10, 13 and 15% nickel extruding alloys are readily produced, in a multitude of shapes, and are also hot forged.

The casting alloys are not included in this survey, but it may be remarked that these often contain, in addition to copper, nickel, and zinc, appreciable amounts of tin and lead, both of which improve the casting properties.

Mechanical Properties of Cold Workable Alloys—While the properties of the nickel silvers will be more completely discussed under individual headings in other articles dealing with specific alloys, a brief summary of the properties as a function of the nickel content is appropriate. Fig. 2 is based on the work of Cook¹ who presents comprehensive and sys-

Fig. 1 shows in a general way the composition ranges of the nickel silvers, although in any given field it should be realized that the commercially important alloys are confined to relatively small areas. The cold working alloys which possess the face-centered cubic structure designated as alpha contain from 7-30% nickel. In general, as the nickel content is increased the zinc content is lowered and a constant copper content of 60-65% gives alloys which are commercially practical.

One of the most widely used of the wrought nickel silvers is "18% nickel silver"

containing about 18% nickel, 17-20% zinc, balance copper. In some instances about 1% of lead is added to improve the machinability, particularly when the alloy is in rod form.

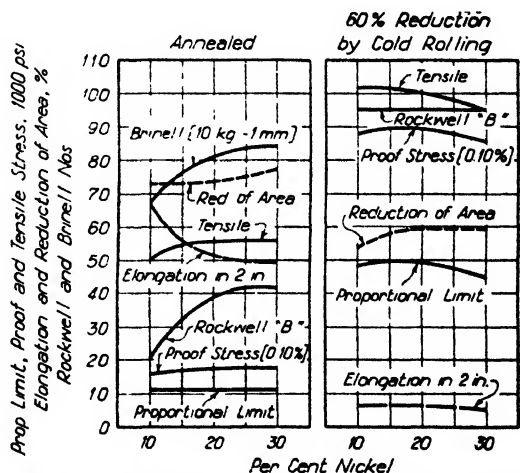


Fig. 2—Properties of nickel-silver of varying nickel content; copper 62% (Cook¹).

*Metallurgist, The International Nickel Co., Bayonne, N. J.

tematic data on the hardness and mechanical properties as affected by cold work, and the annealing characteristics, of seven nickel silver alloys of sensibly constant copper content (60-65%), with nickel ranging from 10-30%.

In the annealed condition the properties increase with the nickel content, but after 60% reduction by cold rolling, changes in the nickel content between 10-30% have little effect. After a 90% reduction by cold rolling Cook finds that the lowest hardness value is obtained at the highest nickel level, suggesting that the extent of work hardening varies inversely with the nickel content at least in this range. The same author presents annealing curves to show that the recrystallization temperature increases with the nickel content, and as in brass, decreases as the cold work performed before annealing is increased. Cook's data³ on thermal conductivity, electrical resistivity and thermal expansion follow:

Nickel, ± 1%	Copper	Zinc	Specific Resistance Microhms- cm ³ ^a	Coefficient of Thermal Expansion 0-400°C. × 10 ⁶ ^a	Thermal Conductivity cal./cm ² /cm/ °C./sec. ^b	Temperature Coefficient of Thermal Conductivity	
10	60-65	25-30	20.71	17.0	0.089	0.108	+0.00123
12	"	23-28	22.32	16.8	0.072	0.090	+0.00124
15	"	20-25	24.79	16.8	0.064	0.081	+0.00148
18	"	17-22	27.55	16.8	0.054	0.065	+0.00114
20	"	15-20	29.03	17.4	0.052	0.063	+0.00120
25	"	10-15	33.65	17.6	0.049	0.060	+0.00124
30	"	5-10	37.89	17.8	0.046	0.056	+0.00120

*Hard drawn 0.057 in. wires (84% reduction in cross section).

**5 x 1/2 in. cylinders, in annealed condition.

***1 in. diameter cast rods machined to 1/2 in. diameter.

Effect of Composition on Color.⁴—Nickel is the most important element in developing whiteness. Zinc in the presence of sufficient nickel also exerts a definite though less vigorous decolorizing influence. The relationship between composition and color of nickel-silvers containing 15-30% of nickel and 0-40% of zinc is schematically depicted⁴ in Fig. 3. There is of course no sharp transition from one field to the next, the colors merging gradually. The shaded area indicates the region of approximately white alloys. Colors are relative and some alloys outside the area, when viewed alone, will be "white" to all intents and purposes. For example, a 20% nickel, 15% zinc alloy possesses a white color when viewed by itself and it is only by placing in juxtaposition with alloys nearer the shaded area that its faint yellow cast is visible. It will be noted that as the nickel content is increased, less and less zinc is required to obtain a white alloy and at 30% nickel, 5% of zinc produces an essentially white alloy. At 13% nickel, upwards of 40% of zinc is necessary to secure whiteness.

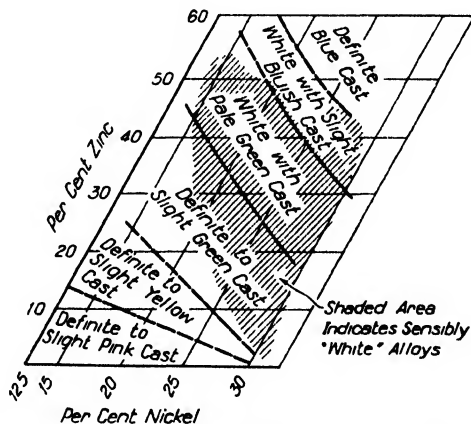


Fig. 3—Color trends of copper-nickel-zinc alloys

In some instances, the ability to produce subdued color tints by suitable adjustment of the copper, zinc and nickel contents of the alloy offers interesting possibilities in decorative metal work, and is of interest to the architect. By suitable juxtaposition subdued color contrasts can be obtained using extruded, cast, rolled, and drawn sections.

Uses.—Nickel silver is used as a base for electroplated silverware, and for rolled gold plate in the jewelry industry, for architectural applications and ornamental metal work; for certain types of food handling equipment, marine fittings, and numerous other applications where a combination of a white color and a useful degree of corrosion resistance are required. Nickel silver is used extensively in

strip form for spring elements, especially in electrical relays, where its mechanical properties and ease of spot welding contacts makes it particularly advantageous.

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Properties of Wrought 18% Nickel Silver (Copper-Nickel-Zinc Alloy)

By R. A. Wilkins*

Composition and General—The wrought 18% nickel silver alloys are predominately white in color, with strength, hardness and general corrosion resistance superior to the usual brasses.

The data herein apply, unless otherwise stated, to an alloy of the nominal composition, 18% nickel, 18% zinc and 64% copper. Other common 18% nickel silver alloys contain 10% and 27% of zinc. With increasing amounts of zinc, the tensile strength and hardness increase.

Nominal Composition : 64% Copper, 18% Zinc, 18% Nickel
Ready to Finish Grain : ——— 0.015 mm. ——— 0.070 mm.

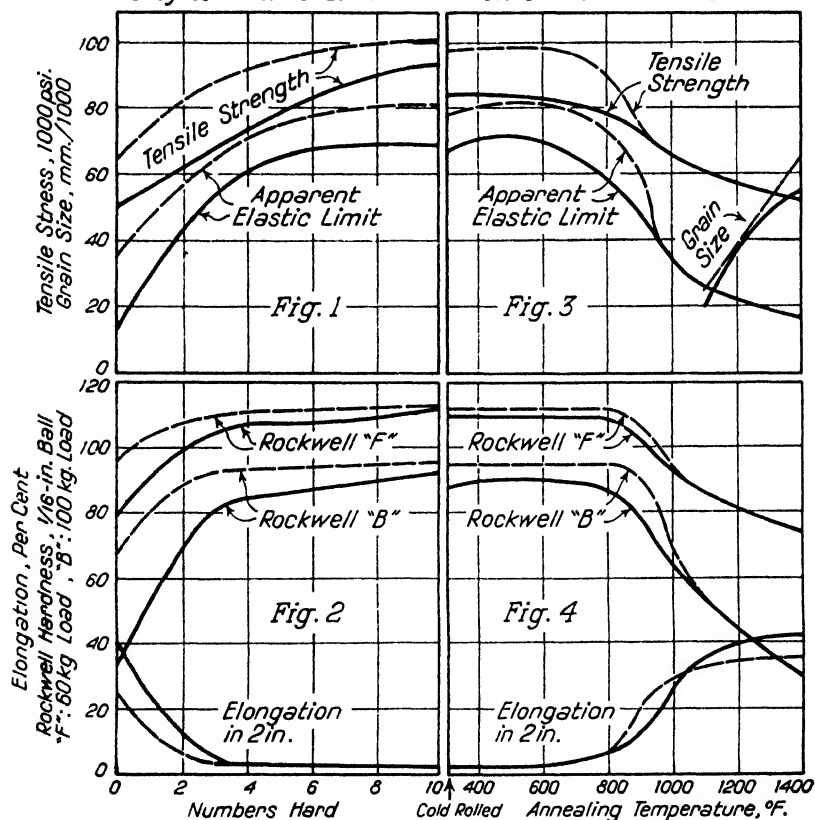


Fig. 1 and 2—Mechanical properties of sheet rolled from metal of two different grain sizes as shown.

Fig. 3 and 4—Mechanical properties of rolled and annealed sheet.

Fabrication is usually accomplished by cold rolling and annealing, hot work being possible only when the zinc content is around 40%, or less than about 10%.

When the combined copper and nickel content is in excess of about 63%, the alloys structurally are simple alpha solid solutions.

Nickel is the most important element in producing whiteness of color, with zinc in a secondary role. For ordinary commercial applications, where whiteness is desired, the 18-18-64 alloy is acceptable.

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Physical Properties of 18-18-64 Alloy

Melting point, °C.....	1110
Density, g./cm. ³	8.72
Linear coefficient of thermal expansion (0-100°C.), °C.....	14.5×10^{-4}
Thermal conductivity, cal./cm. ² /cm./sec./°C.....	0.080
Specific electrical resistance at 20°C., microhms/cm. ²	27.55
Electrical conductivity, %, I.A.C.S. at 20°C.....	5.91
Modulus of elasticity.....	19.5×10^4
Endurance limit at 10 ⁸ cycles,* psi.....	17,500-21,500

*For an alloy of nominal composition, 18% nickel, 26% zinc, and 56% copper. Smaller value, annealed; larger value, 37% and 69% cold work.

Fig. 1 and 2 show the mechanical properties of sheet samples rolled from stock of two different grain sizes after varying degrees of cold work.

Fig. 3 and 4 show the physical properties of annealed material. Specimens were rolled 6 B&S gage numbers prior to finish annealing from stock of two different ready-to-finish grain sizes as indicated.

Workability—The wrought 18% nickel-silvers as indicated by the mechanical properties of annealed material, possess excellent ductility and as a result can be readily drawn, stamped, cold forged, coined, spun and otherwise fabricated.

The 18% nickel-silvers can be readily hard and soft soldered and joined by any of the conventional methods.

These alloys, while not as easy to machine as special free-cutting brasses, machine as well as the copper-zinc alloys to which they are structurally equivalent. Where special cutting properties are required, special alloys containing small amounts of lead are available.

Applications—Large quantities of 18% nickel-silver are used for plated silverware. Hardware, architectural details, ornaments, springs, resistance wire, and chemical equipment.

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Properties of Wrought Leaded Nickel Silver

By T. C. Merriman*

General—Where lead is alloyed with nickel silver (copper-base alloy with zinc and nickel) it is usually done to promote machinability. Ease of machining is obtained at the expense of ductility; and in hard to spring tempers at the expense of strength. Leaded nickel silvers have practically all the advantages of the lead-free alloys of this type so far as color, resistance to corrosion and durability are concerned.

Composition—The three principal grades are 10, 12 and 18% nickel. In rod "full leaded" means 1% lead, but in sheet 10% and 12% "full leaded" usually means 2% lead. The grade (10, 12 or 18%) indicates nickel content, the balance being copper and zinc in the ratio of about two to one in the 10% and 12% nickel grades and about three to one in the 18% grade. Typical compositions are as follows:

Grade	Form	Copper, %	Zinc, %	Nickel, %	Lead, %
10 %	Rod	60	29	10	1
10 %	Sheet	60	28	10	2
12 %	Rod	60	27	12	1
12 %	Sheet	60	26	12	2
18 %	Rod	62	19	18	1
18 %	Sheet	62	19	18	1

Physical and Mechanical Properties

Specific gravity.....	8.7-8.8
Weight per cu. in.....	0.32 lb. approx.
Color.....	Yellow white to silvery white
Electrical conductivity.....	5.7-7% I.A.C.S.
Tensile Strength.....	55,000-120,000 psi. (rod)
Tensile Strength.....	54,000-95,000 psi. (sheet)
Elongation in 2 in.....	0.5-55%
Rockwell hardness.....	B 35-90 (sheet)

Typical values showing the variation of tensile strength and elongation for the 10% and 18% grades of leaded nickel silver at different tempers are shown in Fig. 1 for cold drawn rod, and in Fig. 2 for cold rolled sheet.

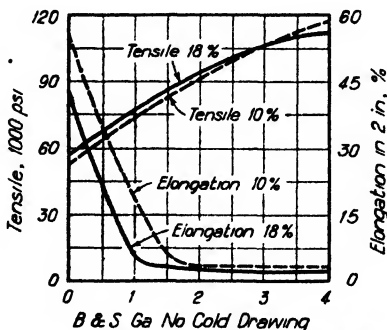


Fig. 1—Tensile properties of cold drawn leaded nickel silver rod.

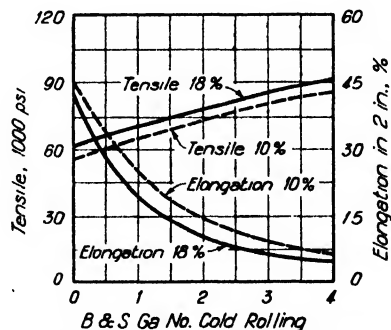


Fig. 2—Tensile properties of cold drawn leaded nickel silver sheets.

Working—Leaded nickel silvers are hot short, and must be cold worked all the way from the chill mold casting. In general less severe reductions must be employed than are feasible for nonleaded nickel silver, both per operation and per cumulative cold reduction between anneals. Although these alloys can be cold worked to what might be called spring temper, there is little object in working either rod or sheet

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more than 4 B. & S. gage numbers hard, since the slight gain in strength is more than nullified by a tendency to brittleness.

Annealing—Leaded nickel silvers are very sensitive to heat, and while the nickel content suggests high temperatures, the lead will not permit, so a compromise is necessary. It is essential to bring the alloys up to heat slowly, and also to cool slowly. The importance of this cannot be overemphasized as fire cracking frequently results from neglect of such precautions.

Uses—Leaded nickel silvers find their principal uses in builders' hardware such as screws, keys, valves, nuts, bolts, lock parts.

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Properties of Copper-Tin-Zinc Alloys

(88-10-2 and 88-8-4)

By Lewis H. Fawcett*

General—The casting composition known as 88-10-2 consists of approximately 88% copper, 10% tin, and 2% zinc. It is an ancient alloy which is still popular and important. The alloy 88-8-4 is a modification of 88-10-2. Both compositions are also known commercially as Government bronze, composition G, gun metal, Admiralty gun metal, and zinc bronze.

The importance of gun metal is due to a combination of properties, such as strength, toughness, bearing qualities, uniform shrinkage and contraction, good casting characteristics, and resistance to sea water corrosion and other similar severe conditions. It has a fine grained, more or less equiaxed crystalline exterior surface, with pleasing full red color, which will take a high polish. This fine grained surface is an aid in the prevention of leakage (if too much of it is not removed by machining) when gun metal castings are subjected to hydrostatic pressure.

Extremely slow cooling of gun metal, because of high pouring temperature or a large cross section of metal, is apt to result in hard spots caused by the local presence of a very high percentage of tin, indicating that the delta constituent, instead of being evenly distributed, has formed in large masses, making the machining of the casting very difficult. The usual chemical analysis may not reveal this condition. The lower tin content of 88-8-4, as compared to 88-10-2, reduces this tendency on account of a smaller amount of the alpha-delta eutectoid being present and consequently less chance for inverse segregation or liquation.

Gun metal is an excellent steam and structural bronze which may be used for expansion joints, pipe fittings, gears, bolts, nuts, valves, pump pistons, castings, bushings, bearings, and, in general where strength and resistance to salt water corrosion are required. It is extensively used in naval and other marine work.

Composition—Uniform composition and freedom from impurities are essential in obtaining maximum mechanical properties and consistent service. Where the best properties are desired, the alloy should conform to the following range of elements, which is not a specification but an ideal practical manufacturing range of composition:

Copper	87.0-89.0
Tin	9.5-10.5
	or
	7.5- 8.5
Zinc ..	1.5- 2.5
	or
	3.5- 4.5
Lead	0.30 max.
Iron	0.10 max.
Nickel	0.75 max.
Phosphorus	0.05 max.
Sulphur	0.05 max.
Antimony	0.25 max.
Aluminum	None
Other elements.....	0.15 max.

Effect of Major Constituents—Increase of tin will cause an increase of the amount of the delta constituent, which will result in increased hardness and stiffness of the alloy. An increase of zinc tends also to increase the hardness and stiffness, but to a much smaller extent than an increase of tin.

Effect of Minor Constituents

Lead—Seldom, if ever, does lead add strength to a copper alloy. On the contrary, it generally detracts from the strength and its action on gun metal is no exception to this fact. Hardness is also reduced by the addition of lead, but machinability is improved by a very small amount of this metal. One-half per cent lead will make gun metal free cutting, but it is better practice to keep the lead content below this figure in foundry production, because of the liability of exceeding this amount

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by the pyramiding of the lead content by the re-use of scrap. Lead over 0.50% does not give proportional improvement in the machinability. One-half per cent lead will also prevent checks or cracks at the junction of a boss and the body of the casting when a sufficient fillet has not been provided. In a case of this kind it would aid in pressure tightness.

Iron—Iron will increase the hardness and is especially objectionable on account of its tendency to produce hard spots which increase the difficulty of machining.

Nickel—A small amount of nickel has a tendency to decrease the grain size and its presence is beneficial rather than detrimental to the casting properties of the metal, and does not adversely affect the resistance to corrosion or wear. In the case of 88-10-2, 0.50% of lead may reduce the hardness. Three-quarters of a per cent of nickel will not materially affect the hardness. One-half per cent lead with 0.75% nickel has a tendency to maintain the normal hardness of 88-10-2 with the increased machinability due to lead. Nickel is not generally added to 88-10-2.

As 88-8-4 is normally somewhat softer than 88-10-2, an addition of 0.50% lead is not likely to affect its hardness, although it will act to increase the machinability. An addition of 0.75% nickel has a tendency to increase the hardness to that of 88-10-2 without materially affecting the casting properties or machinability. This small amount of nickel is also apt to increase the tensile strength and to increase slightly the elastic properties of 88-8-4. One-half per cent lead plus 0.75% nickel tends to increase machinability without loss of the increased hardness due to nickel. It is common practice to add from 0.50-0.75% nickel to 88-8-4.

Phosphorus—It is common practice to add a little phosphorus to gun metal for the purpose of "deoxidizing" the metal. But this practice should not be overdone because phosphorus has a greater effect on increasing the freezing range of this alloy than any other usual addition. It is difficult to produce good sound sand castings from an alloy with increased or varying amounts of phosphorus causing an increased or uncertain freezing range. No more than 0.05% of phosphorus should be added. Also, above this figure phosphorus is apt to cause the appearance of free Cu_3P with a reduction in mechanical properties and will result in poorer surface appearance and increase cleaning costs.

Sulphur—While there is little definite information on the effect of sulphur, it is generally considered doubtful practice to permit this impurity to exceed 0.05%, if the best results are desired.

Antimony—Antimony, while undesirable and never deliberately added to this alloy, will ordinarily cause no trouble if kept below 0.25%.

Aluminum—The presence of aluminum is very objectionable and it should be most rigorously excluded. During the melting of gun metal contaminated with aluminum the aluminum forms an oxide which is insoluble and results in alumina inclusions being trapped in the finished castings. Even a trace of aluminum will cause the castings to have a white silvery skin on their surfaces and its presence is fatal to castings requiring pressure tests.

Other Elements—If other elements including arsenic do not exceed 0.15%, no harmful effects can be attributed to their presence.

Physical and Mechanical Properties—The cast to shape test bar shown in Fig. 1 was employed in determining the properties in tension. Machined tension specimens were of usual form: 0.375 in. radius, 0.505 in. dia. by 2 in. gage length. The ends were threaded and screwed into self aligning fixtures to prevent displacement of Ewing extensometer while determining the elastic properties. Electrical resistivity was determined on these machine specimens prior to making the mechanical tests.

Physical Properties 88-10-2 and 88-8-4

Specific gravity.....	8.5-8.8
Weight per cu. in., lb. (approximate).....	0.314
Patternmaker's shrinkage in. per ft.....	0.15
Pouring temperature (1950°F. Ideal).....	1950-2200°F.
Electrical resistivity (approximate) 88-10-2.....	15.5
88-8-4	13.5

Electrical resistivity as referred to is the resistance, expressed in millionths of an ohm, between opposite faces of a 1 cm. tube of the material. In these units copper has a resistivity of 1.72 at 68°F.

Mechanical Properties

88-10-2 and 88-8-4

Ultimate tensile strength, psi.....	30,000- 45,000
Elastic limit, psi.....	11,000- 14,000
Modulus of elasticity.....	15,000,000
Proportional limit, psi.....	11,000- 14,000
Proof stress, psi.....	13,000- 15,000
Yield point by extensometer, psi.....	18,000- 21,000
Elongation, % in 2 in.....	15-40
Compression of 0.001 in., psi.....	16,000- 17,000
Compression of 0.01 in., psi.....	21,000- 23,000
Compression of 0.1 in., psi.....	41,000- 47,000
Compression of 0.25 in., psi.....	85,000- 97,000
Compression of 0.27-0.29 in., psi.....	100,000
First indication of rupture, psi.....	200,000-300,000
Resistance to impact (Isod), ft.-lb.....	7-14
Brinell hardness number (10 mm. ball, 500 kg. load, held 30 sec.) 88-10-2.....	60-80
88-8-4.....	50-70

Elastic limit was determined as the stress which produced a permanent elongation of 0.00006 in. in 2 in. after the load was released.

Proportional limit was obtained by applying the load in uniform increments of 400 pounds (2,000 psi.) until the elongation under stress ceased to be proportional.

Proof stress was the stress which produced a permanent elongation of exactly 0.0002 in. in 2 in. after the release of the load.

Yield point was determined by applying loads until the specimen had stretched 0.01 in. while under stress.

Compression specimens were machined, 1.129 in. dia. (1 sq.in. area) by 1 in., from 1½ in. dia. bars cast vertically in sand. Measurements were taken with a micrometer caliper, calibrated to 0.0001 in.

Specifications—The following specifications are in general use for gun metal:

A.S.T.M., B60-36.

Society of Automotive Engineers Specification, No. 62.

Federal Specification, QQ-B-691, Grades 5, 6 and 6x.

U. S. Navy Department Specification, 46-M-6.

U. S. Navy Department Specification, 46-B-5.

Federal Specification QQ-B-691, Grade 5, requires a minimum tensile strength of 40,000 psi., and a minimum elongation of 20%. The Navy Department Specification 46-M-6 conforms in technical requirements to Federal Specification QQ-B-691, Grade 5; and Navy Department Specification 46-B-5 conforms to Federal Specification QQ-B-691, Grades 6 and 6x. While the A.S.T.M., Federal, and Navy Department Specification desire 88-8-4, they nevertheless specify a range broad enough to permit the composition 88-10-2. The U. S. Army use Federal Specification QQ-B-691.

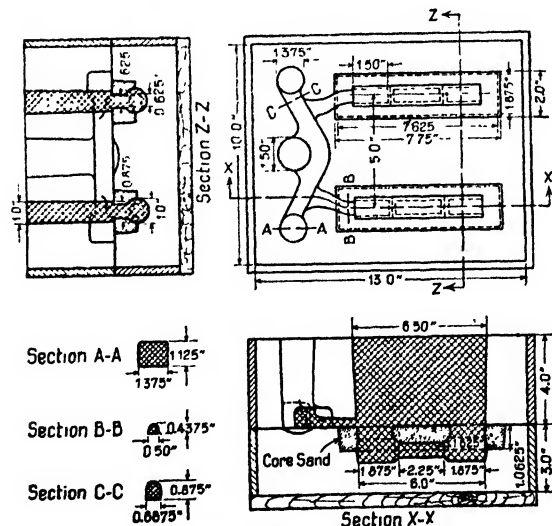


Fig. 1—Cast test bar for bronze.

an abrupt change from one section to another should be avoided by the use of

Design—Gun metal has good casting properties, but to obtain the best results with this alloy, as with other casting compositions, the design should be given very careful thought. The ideal casting should be of uniform thickness throughout at the time of pouring. When uniform cross sections are not possible,

fillets. Also, it is important to avoid excessive machine finish allowances on castings to be subjected to hydrostatic pressure. The chilling effect of the sand mold causes the gun metal casting to have a fine grained exterior, as compared with its interior. To retain this fine grained pressure tight surface, the design should maintain a cast finish for pressure castings when possible, and a minimum allowance for machine finish when machining is necessary.

Melting and Molding—This alloy may be melted in the usual type of bronze melting furnaces. Ingots may be purchased and remelted or the alloy compounded and poured into the molds from the first melting. In foundries compounding their own alloys, when difficulties are encountered or if ideal quality or the highest mechanical properties are consistently required, melting in crucibles placed in a natural draft pit type furnace is recommended. In the crucible process the copper is first melted, protected by a covering of crushed charcoal, if the copper shows indications of wildness; carbon-free manganese is added (about 1 oz. per 100 lb.); then the nickel (if desired) as 50% cupro nickel; then the tin and finally the zinc plus 0.50% for loss. If lead is desired, it should be added and stirred in well just before removing the crucible from the furnace. When phosphorus is used as a "deoxidizer," it may be added with the copper or as a final addition. A flux is not necessary. The melt is poured into cast iron pig molds; analyzed; remelted under a covering of charcoal, preferably without further additions, care being taken to prevent overheating so as not to unduly increase the zinc loss; and then poured into the castings.

Proper pouring temperature in the case of gun metal is most essential. A low pouring temperature is a great help in securing sound castings, pressure tightness and high mechanical properties. Excellent results may be obtained by pouring at 1950°F., but the actual temperature can only be obtained by trial of the particular job. Temperatures above 2200°F. are not recommended.

As gun metal is an excellent casting alloy, with a patternmaker's shrinkage of not more than 0.15 in. per ft., the usual molding practice for bronze is sufficient to secure good results. The molds may be made of either green or dry sand; green sand molds with dry sand cores are quite generally used. On larger castings the molds are frequently skin dried. Heavy sections may be chilled. With care in design, careful melting and low pouring temperature, uniformly sound castings free from defects can be consistently produced.

Test Bar—Federal Specification QQ-B-691 permits the use of either of two types of machined test bars, shown as Fig. 10 and 10A, in Federal General Specification QQ-M-151. The Webbert type is given in Fig. 10 of the specification. Fig. 10A is a modification of the Webbert type (the so-called Crown type test bar) and is very generally used. This bar differs from the Webbert type solely in the connection of the head with the test specimen. The head feeds the Webbert specimen through a web of equal thickness extending the entire length of the specimen, while in the case of the Crown type the head is connected to the ends of the specimen with no contact on the gage length. The thickness of this connecting metal is also greater in the Crown than in the Webbert proper.

The advantages of Crown type are threefold: (1) The elimination of feeding metal on the important part of the casting, in this case the gage length of the specimen; (2) better feeding of the large ends of the specimen which in turn feed the gage length; (3) ease of detaching the head without danger of bending the specimen.

The drawing of the test bar (Fig. 1) in flask gives the dimensions and manner of molding of this type of bar. The dimensions of the specimen and head are taken from Federal General Specification QQ-M-151, Fig. 10A, but as the method of molding is not specified, the molding practice generally used has been included in the drawing. The mold is made of green sand with dry sand cores, which is representative of a large percentage of castings made of this composition. When detached, the test specimens are machined to conform to the dimensions of the standard tension test specimen, 0.505 in. dia. by 2 in. gage length, shown as Type 1 in Federal General Specification for the Inspection of Metals, QQ-M-151.

Heat Treatment—Castings of this type of bronze may be heat treated to correct leakage, due to interdendritic unsoundness, in castings subjected to hydrostatic pressure test; to relieve stresses; or to improve the mechanical properties—especially ductility. The usual heat treatment consists of an anneal at 1400°F. for one hour

per inch of wall thickness (one hour per $\frac{1}{2}$ in. is preferred in some cases) followed by air cooling. Generally only pressure castings are heat treated because the mechanical properties usually specified are readily obtained without risking possible changes in dimensions by the relatively high temperature of an annealing treatment. Castings may be air cooled by opening the furnace door but to reduce distortion to a minimum they should not be removed until cooled to a moderate temperature of 500°F. or less, or they may be placed in pans and removed at the maximum temperature. Heat treatment should be done prior to machining and thus avoid dimensional discrepancies in the finished product.

The ductility of chilled cast bars can be greatly improved by heating at a temperature ranging from 1200-1400°F. for 1 hour per inch of diameter or thickness.

Welding—This type of bronze casting may be welded by the metallic arc process with bare or coated phosphor bronze electrodes. A phosphor bronze electrode of normal composition, except with a 5-7 percent tin content, gives good physical properties in the deposited metal. Such electrodes are wrought phosphor bronze which does not contain zinc. Preheating and annealing are advantageous. Gas welding may also be employed for this purpose when economy permits.

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Properties of Wrought Copper-Tin-Phosphorus Alloys

(Phosphor Bronze)

By H. C. Jennison* and W. S. Girvin†

The copper-tin alloys deoxidized with phosphorus are commonly called "Phosphor Bronze". The phosphorus content varies from a trace to 0.50%. Copper and tin form a complex series of alloys but only the alpha alloys are used for wrought bronzes. The tin content varies from a fraction of 1% up to a maximum of about 11%, depending on the shape of the finished product and the physical requirements.

In sheet form the industry has standardized on three grades which have become known as Grade A, C, and D. Grade A is nominally a 4 or 5% tin alloy, while the C and D grades contain 8 and 10% tin, respectively. This series of alloys is used most extensively for springs and diaphragms because of its higher resiliency and resistance to fatigue. They also have good resistance to wear. Properties of these alloys are given in Table I.

Table I
Properties of Phosphor Bronze

	Melting ^b Point, °C.	Coefficient of Expansion, 25-300°C.	Electrical Conductivity, % I. A. C. S. at 20°C.	Thermal Conductivity ^a	Modulus of Elasticity, psi., $\times 10^{-4}$	Density lb. per cu. in.
Grade A.....	1050	0.0000178	18.37	0.195	15.0	0.320
Grade C.....	1025	0.0000182	13.00	0.150	15.0	0.318
Grade D.....	1000	0.0000183	10.6	0.121	15.0	0.317

^a = Cal. per sq. cm. per cm. per sec. per °C. at 20°C.

^b = Heycock-Neville constitution diagram.

The properties given in Tables II, III, IV, and V are from A.S.T.M. Specification—for Sheet Phosphor Bronze, Grades A, C, and D.

There are also leaded alloys in sheet form, usually containing about 5% tin and from 1-4% lead to make the alloy free cutting and for bearing purposes. Grades A, C, and D are produced in rod form. Grade A is also modified by the addition of lead. The leaded alloys are especially adapted to screw machine work. The two most common have the following nominal composition:

Copper	94%	Copper	88%
Tin	5%	Tin	4%
Lead	1%	Lead	4%
		Zinc	4%

The second alloy is usually made to meet the following physical requirements:

	Min. Tensile Strength, psi.	Min. Elongation in 2 in., %
Up to ¼ in., incl.....	60,000	25
¼-1 in., incl.....	55,000	30
Over 1 in.....	50,000	30

Grade A spring wire is made to the following requirements:

Wire Dia., in.		Tensile Strength, psi., Min.
Over	To and Including	
0.0000	0.0625	130,000
0.0625	0.1250	120,000
0.1250	0.2500	110,000
0.2500	0.3750	100,000

The wrought phosphor bronze alloys are usually cold worked but some of the lower alloys containing less than 2% of tin can be hot worked. The endurance limit of Grades A, C, and D Phosphor Bronze is approximately 25,000-27,000 psi. in the hard state. Because these alloys are refractory they take 25% addition over the regular brass tolerances for sheet and tube.

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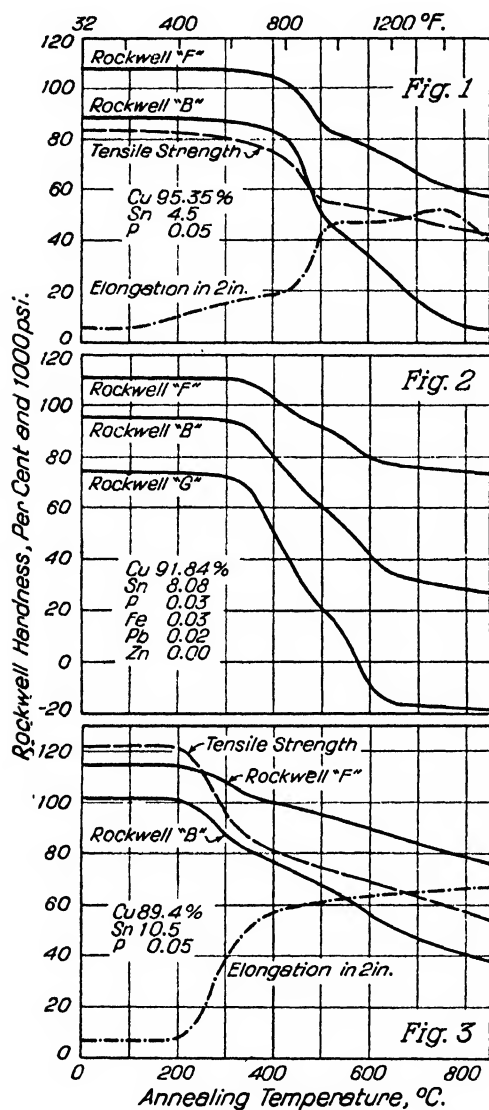


Fig. 1—Phosphor bronze Grade A sheet—gage, 0.040 in. Reduced 50% in thickness by rolling. Annealed $\frac{1}{2}$ hr. at temperature noted. Fig. 2—Same as Fig. 1, but for Grade C. Fig. 3—Same as Fig. 1, but for Grade D.

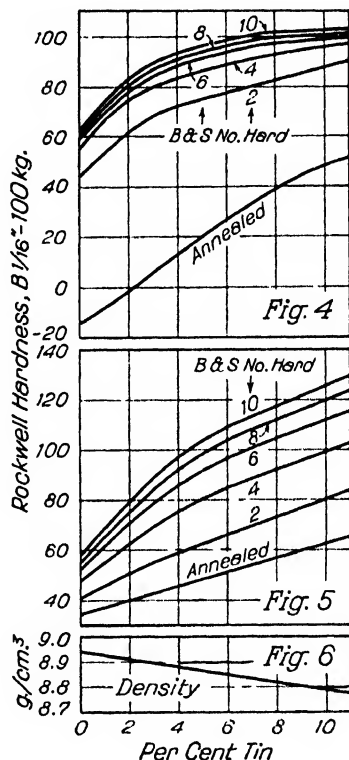


Fig. 4—Rockwell hardness of annealed and cold rolled phosphor bronze sheet, tin 0-11%. Average grain diameter of 0.050 min. and a minimum gage of 0.040 in. Bottom curve represents annealed material, other curves represent same material, but rolled as indicated. Fig. 5—Tensile strength in thousand psi. on same material as in Fig. 4. Fig. 6—Density values for same materials as in Fig. 4.

Table II
Temper Requirements for Grade "A" Phosphor Bronze Sheet

Temper	No. Hard	Thick- ness, in.	Nominal Reduction by Roll- ing, %	Tensile Strength, psi.		Rockwell "B" Hardness		Rockwell "G" Hardness		Rockwell 30 "T" Hardness	
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Soft	0	0.040 and over	0	40,000	55,000	7	50	..	12	..	..
		0.030 and over				..	..	..	..	24	50
		0.020-0.040				0	45	..	..	..	..
		0.010-0.030				..	..	..	..	16	46
Half hard	2	0.040 and over	20.7	55,000	70,000	60	81	20	53	..	..
		0.030 and over				..	..	..	..	57	73
		0.020-0.040				53	78	15	51	..	..
		0.010-0.030				..	..	..	..	52	71
Hard	4	0.040 and over	37.1	72,000	87,000	82	90	55	66	..	..
		0.030 and over				..	..	..	..	71	77
		0.020-0.040				80	88	53	64	..	..
		0.010-0.030				..	..	..	..	69	75
Extra hard	6	0.040 and over	50.0	84,000	98,500	88	94	64	73	..	..
		0.030 and over				..	..	..	..	75	80
		0.020-0.040				86	92	62	71	..	..
		0.010-0.030				..	..	..	..	73	78
Spring	8	0.040 and over	60.4	91,000	105,000	90	96	69	75	..	..
		0.030 and over				..	..	..	..	77	81
		0.020-0.040				88	94	67	73	..	..
		0.010-0.030				..	..	..	..	75	79
Extra spring	10	0.040 and over	68.6	96,000	109,000	92	97	72	77	..	..
		0.030 and over				..	..	..	..	78	82
		0.020-0.040				89	94	70	75	..	..
		0.010-0.030				..	..	..	..	76	80

Table III
Temper Requirements for Grade "C" Phosphor Bronze Sheet

Temper	No. Hard	Thick- ness, in.	Nominal Reduction by Roll- ing, %	Tensile Strength, psi.		Rockwell "B" Hardness		Rockwell "G" Hardness		Rockwell 30 "T" Hardness	
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Soft	0	0.040 and over	0	53,000	67,000	29	70	..	33	..	..
		0.030 and over				..	..	..	..	38	68
		0.020-0.040				20	66	..	..	..	..
		0.010-0.030				..	..	..	..	27	62
Half hard	2	0.040 and over	20.7	69,000	84,000	76	91	47	68	..	..
		0.030 and over				..	..	..	..	67	76
		0.020-0.040				69	88	40	64	..	..
		0.010-0.030				..	..	..	..	63	75
Hard	4	0.040 and over	37.1	85,000	100,000	91	97	69	77	..	..
		0.030 and over				..	..	..	..	76	81
		0.020-0.040				89	95	65	74	..	..
		0.010-0.030				..	..	..	..	73	80
Extra hard	6	0.040 and over	50.0	97,000	111,500	95	100	76	82	..	..
		0.030 and over				..	..	..	..	78	83
		0.020-0.040				93	98	73	79	..	..
		0.010-0.030				..	..	..	..	77	82
Spring	8	0.040 and over	60.4	105,000	118,500	97	102	79	85	..	..
		0.030 and over				..	..	..	..	79	84
		0.020-0.040				95	100	76	82	..	..
		0.010-0.030				..	..	..	..	78	83
Extra spring	10	0.040 and over	68.6	109,500	122,000	98	103	81	86	..	..
		0.030 and over				..	..	..	..	80	84
		0.020-0.040				96	101	78	83	..	..
		0.010-0.030				..	..	..	..	79	83

Table IV
Temper Requirements for Grade "D" Phosphor Bronze Sheet

Temper	No. Hard	Thick-ness, in.	Nominal Reduction by Rolling, %	Tensile Strength, psi.		Rockwell "B" Hardness		Rockwell "G" Hardness		Rockwell 30 "T" Hardness	
				Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Soft	0	0.040 and over	0	58,000	73,000	35	75	..	40	..	..
		0.030 and over				..	..	..	..	40	78
		0.020-0.040				25	71	..	30	..	..
		0.010-0.030				..	..	..	..	29	64
Half hard	2	0.040 and over	20.7	76,000	91,000	78	95	48	75	..	..
		0.030 and over				..	..	..	..	67	80
		0.020-0.040				74	93	38	71	..	..
		0.010-0.030				..	..	..	..	63	77
Hard	4	0.040 and over	37.1	94,000	109,000	94	101	72	83	..	..
		0.030 and over				..	..	..	..	78	82
		0.020-0.040				92	100	68	80	..	..
		0.010-0.030				..	..	..	..	75	81
Extra hard	6	0.040 and over	50.0	107,000	122,000	98	103	79	86	..	..
		0.030 and over				..	..	..	..	80	84
		0.020-0.040				97	102	78	83	..	..
		0.010-0.030				..	..	..	..	79	83
Spring	8	0.040 and over	60.4	115,000	129,000	99	104	81	88	..	..
		0.030 and over				..	..	..	..	81	85
		0.020-0.040				98	103	78	85	..	..
		0.010-0.030				..	..	..	..	80	84
Extra spring	10	0.040 and over	68.6	120,000	133,000	100	105	83	90	..	..
		0.030 and over				..	..	..	..	82	86
		0.020-0.040				99	104	80	87	..	..
		0.010-0.030				..	..	..	..	81	85

Table V
Chemical Composition
(A.S.T.M. Specification B-36-T)

	Per Cent		
	Grade A	Grade C	Grade D
Copper	Remainder	Remainder	Remainder
Tin	3.80-5.80	7.0-9.0	9.0-11.0
Phosphorus	0.03-0.35	0.03-0.25	0.03-0.25
Iron, max.....	0.10	0.10	0.10
Lead, max.....	0.05	0.02	0.02
Antimony, max.....	0.01	0.01	0.01
Zinc, max.....	0.03	0.20	0.02
Nickel, max.....	.....	0.15	.....
Copper plus Tin plus Phosphorus, min.....	99.50	99.50	99.60

Properties of Cast Copper-Zinc-Tin-Lead Alloys

(Alloy 85-5-5-5)

By J. W. Bolton,¹ F. L. Wolf,² and Wm. Romanoff³

The alloy known as 85-5-5-5 is a copper base alloy composed of 85% copper, and 5% each of tin, zinc, and lead, plus or minus certain tolerances. Years ago it was called ounce metal, because the usual mixture was 1 oz. each of tin, zinc, and lead to each pound of copper—which roughly approximates 85-5-5-5. Today this alloy is widely known as eighty-five three fives. The derivation of this appellation is obvious.

The alloy is used for general utility purposes where reasonable strength and noncorrosive properties are demanded. It is rather widely used in the manufacture of many pressure castings, in some cases for bearings, and for miscellaneous engineering applications at temperatures not exceeding about 450°F.

The eighty-five three fives alloy is one of the most widely used nonferrous sand cast alloys. The alloy possesses the attributes of fairly low cost, good physical properties, good casting properties, and easy machinability.

The microstructure of the matrix of this alloy closely resembles that of the binary alloy of copper with 7 or 8% tin. The coring formation, characteristic in sand cast alloys of this type, is well pronounced. As a rule, the alpha-delta eutectoid is not found, or occurs only in small amounts. The characteristic cored matrix contains many small globular particles of lead. Lead is relatively insoluble in the matrix and usually is found in the dendritic fillings.

Specification—Most modern specifications for this alloy are based upon the A.S.T.M. specification B 62-36, the chemical and physical requirements of which are:

	Desired	Min.	Max.
Copper, %	85.00	84.00	86.00
Tin, %	5.00	4.00	6.00
Lead, %	5.00	4.00	6.00
Zinc, %	5.00	4.00	6.00
Iron, %	..	....	0.25
Nickel, %	..	....	1.00
Phosphorus, %	..	....	0.05
Tensile strength, psi.	.....	.....	30,000 min
Yield point, psi.	.....	.....	14,000 "
Elongation in 2 in., %	.....	.....	20.0 "

Most 85-5-5-5 is made from refined ingot which may be purchased under A.S.T.M. specification B 30-36 Alloy Grade 4. The chemical specifications for ingot metal are different than and should not be substituted for those for castings.

The most important factors influencing the physical properties of castings made from alloys of this type are soundness and freedom from internal porosity. The underlying causes of unsoundness and the methods for correcting are subjects which are touched upon in the data sheets of the A.F.A. dealing with this alloy. *The Foundry* has published a summary of this subject in serial form in the issues of Aug. 1, Sept. 1, Oct. 1, and Nov. 1, 1930.

Effects of Major Constituents—Increase of tin increases the hardness and stiffness of the alloy. Increase of zinc also acts in this direction, but to a less degree than an increase of tin. Increase of lead gradually decreases the strength, increases machinability, and lowers elongation.

Impurities

Iron—Free iron in appreciable amounts causes hard spots. Alloyed iron, within the specification, has no pronounced effect on the alloy. High iron increases hardness very materially, particularly when not in combination or when nickel is present. In any quantity it increases the electrical resistivity.

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²Technical Supt., Ohio Brass Co., Mansfield, Ohio.

³Technical Supt., H. Kramer & Co., Chicago.

Nickel—Within the maximum specified, nickel is not detrimental. Large amounts of nickel raise the initial freezing point and may increase the sluggishness of the metal. When sufficient nickel is added the cored structure is broken up and the color of the alloy changes. It then is not 85-5-5-5 alloy, properly speaking.

Phosphorus—Phosphorus is usually employed as a deoxidizer. For this purpose not more than a trace need be retained in the final alloy. The maximum amount permitted under the specification lengthens the freezing range of the alloy and increases the fluidity an appreciable degree. Phosphorus increases the hardness and in some cases has a tendency to discolor the surface of the castings. It also increases the tendency of the castings to "burning in" and consequent rough appearance.

Aluminum—Aluminum is an extremely dangerous impurity and even a few hundredths of a per cent has a detrimental effect on the physical properties of the alloy, because it makes the castings very unsound. Aluminum apparently alters the crystallization characteristics of the alloy very markedly. Even very small amounts sometimes cause lead sweat.

Silicon—Silicon is also a dangerous impurity. As much as 0.03% is likely to produce decided unsoundness. It apparently goes into solid solution and affects the crystallization characteristics of the alloy. In leaded alloys, the tendency toward formation of dross from interaction of silicon and lead compounds is pronounced.

Sulphur—Sulphur within the amounts allowed by the specification is not likely to cause trouble. Sulphur promotes sulphide inclusions, which if not too great in amount do not seriously impair the properties of the alloy.

Antimony—Antimony up to the maximum allowed by the specification apparently does not cause trouble.

Physical Properties—The ultimate tensile strength minimum of the specification is 30,000 psi. Average foundry practice is about 33,000 psi. However, foundries maintaining rigid technical control are able to materially exceed this average.

The modulus of elasticity of this alloy must be established arbitrarily, since no exact proportional limit is apparent. At 8,000 psi. stress the apparent modulus is about 13×10^6 psi.

The yield point in the specification is given as 14,000 psi. min. stress required to produce 0.01 in. strain in a 2 in. gage length. In a sound, well made alloy this point will be found to average about 15,500 psi. However, there is a sharp "elbow" or change in curvature in the stress strain diagram somewhat above 10,000 psi. and proportional limit is about 8,000 psi.

The min. elongation in 2 in. gage is 20%. On a good sound alloy the average will be nearer 25%.

At elevated temperatures the strength while under load drops gradually until 400°F. is reached, rather rapidly from 400-500°F., and very rapidly above 500°F. Above 500°F. the drop in tensile strength is very rapid. The above suggests that this alloy, in common with others of its type, should not be used much above 450°F. unless a reasonably large safety factor is employed. Long exposure to temperatures above 450°F. causes embrittlement.

The Brinell hardness ranges from about 48-58 (500 kg. load).

Rockwell using $\frac{1}{8}$ in. ball is about 65-75.

Specific gravity of sand cast alloy at 25°C. is about 8.7. This varies according to the soundness.

Specific gravity of chill cast alloy at 20°C. is 8.9.

Weight per cu.in. 0.314 lb.

Pattern makers' shrinkage usually is taken as $\frac{1}{8}$ in. per ft.

The linear contraction 20-900°C. is 18.4×10^{-6} .

The volume shrinkage 20-900°C. is 5.5%.

The solidification shrinkage is 4.9%.

Izod test is about 9 ft.-lb. (average of several tests).

Electrical conductivity (% of annealed copper at 20°C.) 16.4.

Creep tests have shown that the 85-5-5-5 alloy is quite inferior to the A.S.T.M. B 61-36 type valve or steam bronze at 500°F. The 85-5-5-5 alloy shows rapid and continuous creep at load of 3,000 psi.¹ at temperature of 500°F. (Ref. Proceedings A.S.T.M., Vol. 35, Part II, p. 213.) There is no danger of lead sweat in this alloy within the temperature range indicated if the alloy is made properly.

¹Proc., A.S.T.M., 1935, v. 35, p. 213.

Properties of Wrought Copper-Zinc-Tin Alloys

(Admiralty Metal)

By William B. Price*

History—Admiralty metal was originally developed by the British Admiralty for use as a condenser tube material. Copper-zinc alloys which were used for condenser tubes before the inception of Admiralty metal were either Muntz metal, containing 60% copper and 40% zinc or an alloy of 70% copper and 30% zinc. Admiralty metal rapidly superseded the 70:30 mixture and also much of the Muntz metal which had been used under less severe service conditions. The consumption of this material has continued to grow since its beginning and it is now, without question, the most common of all nonferrous tube mixtures.

In recent years many special alloys have been developed and are now offered by nonferrous tube producers. These include the copper-nickel alloys, aluminum brasses and bronzes, red brasses, and modifications of Admiralty. While these materials are of great value in a great many specific installations, Admiralty metal at present continues to be in considerable demand.

Properties—The chemical composition of Admiralty metal as specified by the A.S.T.M., United States Navy, and others, is as follows:

Copper, not less than 70.00%; tin, 0.90-1.20%; lead, not over 0.075%; iron, not over 0.06%; and zinc, remainder.

Physical Properties of Admiralty Metal

	Soft	Hard
Tensile strength, psi.....	50,000 (min.)†	90,000 (min.)†
Yield strength, psi.....	23,000	88,000
Endurance limit, psi.....	15,000	
Modulus of elasticity.....	15,000,000	
Elongation, % in 2 in.	60-75	2 min.
Reduction in area, %.....	70 min.	55 min.
Rockwell hardness ($\frac{1}{16}$ in. 100 kg.).....	B 10	B 95
Brinell hardness (10 mm. 500 kg.).....	50	190
Coefficient of expansion (range 77-572°F).....		0.0000112
Thermal conductivity B.t.u./sq.ft./in./sec /°F ..		0.218
Electrical conductivity (% of copper).....		25
Weight.....	309 lb./cu in	8.55 g/c.c .
Melting point.....	1715°F.	934°C.

†Stress in a material at which there occurs a permanent deformation of $\frac{1}{2}\%$ on a 2 in. gage length.

The above table gives the normal commercial tensile strength limits of hard and soft Admiralty tubing. Finish annealed tubing usually will average a tensile strength of approximately 55,000 psi. or higher. Hard drawn wire can be manufactured having a tensile strength in excess of 125,000 psi.

The value of the endurance limit is an average result of tests on annealed Admiralty metal. Under combined corrosion and repeated stress, this value would be lower. Cold working raises the endurance limit of Admiralty metal and, in general, it may be stated that the stronger the material is in tension, the higher are the endurance properties.

The figure given for coefficient of expansion is taken from Scientific Paper No. 410, U. S. Bureau of Standards, and represents an average value for the given range of temperatures.

Machinability—Admiralty metal machines similar to mild steel and should be cut at speeds and feeds approximately 50% of those used for free turning leaded brass. Cutting speed should not exceed 200 surface feet per minute. High speed, steel or carbide tools are recommended.

Physical Properties at Elevated Temperatures—Fig. 1 illustrates the physical properties of Admiralty metal at elevated temperatures. Determinations were made on standard high temperature tensile test specimens machined from $\frac{3}{4}$ in. cold drawn rod. The variation in properties with increasing temperature is normal for non-leaded alpha brasses up to 800°C. At this temperature a second phase (tin-rich)

*Scovill Mfg. Co., Waterbury, Conn.

begins to separate at the grain boundaries in a molten or semimolten condition and makes the alloy "hot short". These data indicate the hot workability of the mixture and should not be used to predict its service at elevated temperatures.

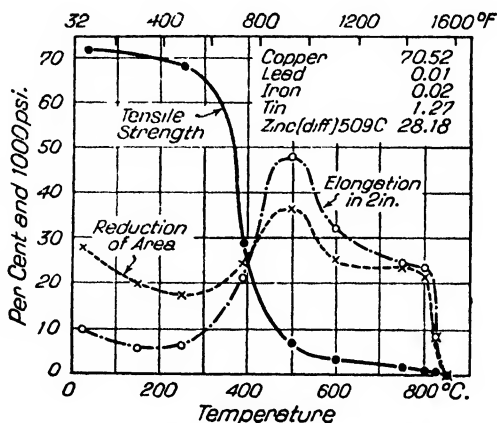


Fig. 1—Properties of Admiralty metal at elevated temperatures.

Uses—Wrought Admiralty metal is made in the form of rod, wire, sheet, and tubing. The alloy is easily worked and combines ductility, malleability, and strength with a pleasing greenish yellow color and good resistance to general corrosion. Because of these desirable characteristics, it is frequently substituted for yellow brass rod, wire, or sheet. By far the greatest application of the alloy is, however, in the form of tubes and tube fittings. As such it is used in condensers, preheaters, evaporators, and air conditioning units, in contact with salt or fresh water, oil, steam and other liquids.

Specifications—Many specifications are in use to control the purchase of Admiralty metal tubing. Among these are United States Navy Spec. 44T7e, United States Federal WW-T-756 and A.S.T.M. B44-33. The latter specification is most generally used in the trade and represents the joint opinions of many producers and users.

With respect to the difference in British and American practice, namely, the use of hard drawn and finish annealed tubing, it is quite generally accepted that each type has its particular merits. The hard drawn British tubes better resist mechanical forms of attack, air impingement, and erosion. The soft American tubes better resist chemical and electrochemical forms of corrosion.

Corrosion Resistance—The problems of corrosion resistance are by nature complex. Each installation should, where possible, be treated as an individual case. In presenting a problem of tube corrosion to a tube producer no detail of the case history should be overlooked.

Bearing in mind the limitations, it can be stated that, in general, Admiralty tubing can be used with "fair to excellent" results in practically all types of industrial heat exchanging equipment in contact with circulating water, steam, or oil at operating temperatures under 500°F.

Tinning of one or both tube surfaces subject to attack frequently is of great value in improving service life of Admiralty used under adverse conditions.

Some producers claim that tubes finished with an oxidized surface are superior in corrosion resistance to those acid cleaned.

Properties of Cast Copper-Zinc-Lead-Tin Alloys

(Medium Red Brass)

By H. M. St. John*

Classification—Medium red brass alloys contain from 2-3% of tin, 7-10% of lead, 8-15% of zinc, balance copper. Alloys in this group cast well, are readily machinable, and are in general suitable for pressure work where pressures do not greatly exceed 40 or 50 psi. at temperatures not over 250°F. They are also suitable for a great variety of brass castings where it is desired to obtain a red color at low cost, and when the mechanical properties are not important. Radiator valves, low-pressure steam fittings, and low-pressure water fittings are among the products made from alloys of this general composition.

Typical Composition and Physical Properties—A typical alloy has the following composition, in per cent: Cu 77, Zn 10, Pb 10, and Sn 3. Representative physical properties¹ are as follows:

Tensile strength, psi.	27,100
Yield point, psi.	17,900
Per cent elongation in 2 in.	11.5
Brinell hardness (500 kg. 10 mm. ball)	89

A modification of this alloy with a composition in per cent of Cu 78, Zn 9, Pb 10, Sn 2.5, and Ni 0.5 has the following properties:

Tensile strength, psi.	29,000
Yield point, psi.	17,200
Per cent elongation in 2 in.	16
Brinell hardness (500 kg. 10 mm. ball)	57

In the A.S.T.M. Specification B30-36, copper-base alloys in ingot form for sand castings alloy No. 9 is listed as follows: Cu 79-80%, Sn 2.5-3.5%, Pb 6.25-7.75%, Zn 7.5-9.5%, P 0.03% max., Sb 0.25% max., Fe 0.35% max., Ni 0.50% max., S 0.08% max., Al none, Si 0.05% max., and total impurities (other than nickel) 0.50%.

It is further stated that the following properties may be expected:

Tensile strength, psi.	22,000 to 28,000
Elongation in 2 in., %	10 to 15
Brinell hardness No.	50 to 55
Pattern maker's allowance for shrinkage, in. per ft.	0.1875 (A)
Weight, lb. per cu. ft.	540

Influence of Nickel—The addition of 0.5% nickel increases the elongation, densifies the structure (so that the interior of a moderately thick section is almost as fine-grained as the part close to the outer skin), lowers the optimum pouring temperature, and improves the machinability.

The influence of nickel on the pouring temperature is pronounced and seems to increase the fluidity at temperatures close to the freezing point. The pouring range is slightly decreased due to the effect of nickel in raising the actual freezing point. Castings of moderate size and section which may best be cast at 2200-2100°F. in the unmodified alloy cast equally well at 2125-2050°F. when 0.5% nickel is included in the composition.

Machining Qualities—The machining qualities of the alloys have been compared by a drilling test in which the time required for a weighted $\frac{3}{8}$ in. drill to pass through a $\frac{3}{8}$ in. thick test block was measured and compared with the time required for a standard block of the same thickness. Ten holes were drilled in each block and the average taken. Arbitrarily assigning the value of 100 to the modified alloy (0.5% Ni), the following results were obtained as the average of a large number of tests:

Alloy Composition, %					Machinability No.
Cu	Zn	Pb	Sn	Ni	
78	9	10	2.5	0.5	100
77	10	10	3	—	108
85	5	5	5	—	145

As compared with the alloy containing 0.5% Ni, it takes 8% longer to drill a hole through a given thickness of alloy 77:10:10:3 and 45% longer through the same thickness of the alloy 85:5:5:5. The difference in machinability may be ascribed

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¹Average of six tests on an alloy made from 50% new metal and 50% re-run metal.

to the difference in tin content. The substitution of 0.5% Ni for an equal proportion of tin improves the machinability without impairing other mechanical properties.

Properties at Elevated Temperatures—Exact data with respect to properties of these alloys at elevated temperatures are lacking, but it is well known that alloys containing as much as 10% lead cannot safely be used much above 250°F. unless at higher temperatures the pressure to which they are exposed is slight. If the percentage of lead is decreased, the temperature at which the alloy can be used increases somewhat.

Resistance to Corrosion—Generally speaking, all of the alloys in this group have about the same resistance to corrosion as the 85:5:5:5 alloy. As ordinarily used, the only point of real importance is that they do not stand up well against alkaline waters.

Effect of Alloying Elements—A large number of alloys, varying in composition within the range included here, are being made by different foundries; each one seems to have its favorite. In general their properties are much the same but there is, naturally, some variation due to change in the principal constituents. Increasing the proportion of zinc hardens the alloy, slightly increases its strength and makes it more difficult to machine. Increasing the proportion of tin hardens the alloy, substantially increases both strength and yield point and makes it more difficult to machine. Increasing the proportion of nickel (to a maximum of 2.0%) toughens rather than hardens the alloy, substantially increases the strength but not the yield point and does not greatly affect the machinability. Increasing the proportion of lead above 10% is undesirable because of difficulty with lead sweat. This segregation of lead on the surface of the casting cannot be prevented by thoroughly mixing before pouring the castings, since it is caused by the separation of lead during solidification followed by extrusion of the still molten lead to the surface of the metal as a result of contraction. This is evidenced by the fact that the lead covered surfaces are almost always found on the cope of the casting.

In order to avoid sweat at a 10% lead content the tin should be held at 2.25% or above, the zinc at 6% or above. In alloys of this class nickel does not seem to have much influence on lead segregation, whereas both tin and zinc are important. If the proportion of lead is decreased below 10%, the machinability and density of the alloy are both impaired but the danger of lead sweat decreases. With such reduction in lead content the proportion of tin may also be reduced and the strength of the metal maintained by increasing the zinc.

Impurities—The principal impurities to be considered are aluminum, magnesium, silicon, iron, sulphur, antimony, and phosphorus. Aluminum is a very undesirable impurity and should be under 0.01%. Magnesium-copper is an effective deoxidizing agent, but cannot be used with safety because there must be no residue of metallic (unoxidized) magnesium in the alloy, certainly not more than 0.01%. The presence of silicon to the extent of 0.01% or more results in segregation of lead, accompanied by a weak, brittle structure with intercrystalline fissures. Iron should not exceed 0.30%, preferably 0.20%. Sulphur should be under 0.10%, preferably 0.05%. Less than 0.20% antimony has a noticeable effect on foundry brass containing 10% lead; 0.15% should be considered a maximum. Phosphorus is permissible up to 0.05%.

Corrosion Resistance of Copper and Copper-Base Alloys

By H. L. Burghoff* and N. W. Mitchell*

Metallic copper is resistant to alkaline solutions, except those containing ammonia. Its attack by mineral and organic acids is dependent largely upon the presence of an oxidizing agent in solution. Copper also resists oxidation by water vapor at high temperatures and has good resistance in general to most salt solutions. Under certain conditions, copper or copper alloys acquire a film which may be protective, but may be damaged by the high velocity of the solution or from other causes.

Copper has poor corrosion resistance to sulphur and sulphur compounds. Alloying the metal with zinc to produce brasses greatly increases the resistance to sulphur. In general, the lower the copper content of the brass, the better the resistance to sulphur compounds.

A considerable variation in corrosion resistance occurs with the change in copper content in the copper-zinc alloys (brasses). Those alloys containing less than about 80% of copper are sometimes subject to corrosion in such a manner that the zinc is selectively removed from the alloy. This phenomenon which results in the formation of porous masses or layers of copper in the article undergoing corrosion is called "dezincification."

Dezincification is encountered with corrosive water supplies in plumbing work with alloys such as Muntz metal containing 60% copper and 40% zinc, and "2 and 1" alloy containing 67% copper, 0.5% lead, and 32.5% zinc. It is particularly serious at hot water temperatures, resulting in some cases in very short life of the installation. In condenser tube applications for marine power plants and the oil industries, dezincification occurs with Admiralty brass, which contains 70% copper, 1% tin, and 29% zinc.

Dezincification is avoided by the use of alloys containing more than about 80% of copper. In plumbing work the use of red brass (85% copper 15% zinc) has entirely eliminated failures by dezincification. Red brass appears to possess the greatest general corrosion resistance of the binary copper-zinc alloys, its advantage over copper being a somewhat superior resistance to pitting.

Addition of small amounts of antimony or arsenic have been found to improve the resistance of low copper alloys to dezincification. Although arsenic inhibits dezincification of yellow brass alloys, its use frequently leads to intercrystalline corrosion. The fact that antimony improves the resistance of low copper alloys to dezincification is important in the oil industry in particular where low copper brasses are desirable for good resistance to sulphur and sulphur compounds.

The addition of tin is of lesser but still of essential benefit with regard to dezincification when added to high brass alloys. The addition of tin to Muntz metal, resulting in Naval Brass, improves the resistance of this alloy to sea water and other corrosive solutions. The addition of tin to 70-30 brass, resulting in Admiralty, gives an improvement over the binary alloy.

The accelerated corrosive action occurring in marine and seaboard power station condenser tubes is the result of high water velocity, particularly when considerable air is entrained in the cooling water. This type of attack is known as impingement attack or destructive cavitation. Impingement attack is usually characterized by deep pitting, quite frequently with the pits having the shape of a horseshoe. With the addition of about 2% of aluminum to the ordinary brass alloys, the resulting alloy will form a self-healing film resulting in good resistance to impingement attack.

The common aluminum brass alloy used in condenser tubes for resisting impingement attack contains about 76% copper, 2% aluminum, and 22% zinc. A modification of this alloy contains 82% copper, 2% aluminum, 1% tin, and 17% zinc. The modified alloy in particular has good resistance both to impingement attack and to dezincification.

The commercial copper-nickel alloys include 20% and 30% copper and the so-called nickel silver alloys contain usually 10, 12, or 18% nickel with copper contents of about 65%, and the balance zinc. The copper-nickel and nickel silver alloys have good corrosion resistant properties, including resistance to destructive cavitation or impingement attack. The cupro nickels in particular are used many

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times when conditions are so corrosive that other copper-base alloys have failed to show the necessary resistance. In general, the resistance of this series of alloys increases slightly with the nickel content.

Copper-aluminum alloys, known as aluminum bronzes, have gained a good reputation for corrosion resistance. The commercial alloys of this series contain usually 5, 8, or 10% aluminum with the balance copper.

The tin bronzes, or as they are frequently called, phosphor bronzes, contain up to about 8% of tin with the balance copper. These alloys are used for resisting many corrosive solutions and for plaques and tablets in the form of castings which are exposed to the atmosphere. The usefulness of tin bronzes has been limited by the high cost of the alloys and by the difficulty involved in working them.

A group of alloys which has found wide use is the silicon bronze group of copper-base alloys. These contain about 3% of silicon with or without about 1% of a third element such as zinc, tin, or manganese. The usefulness of these alloys is due to the good corrosion resistance, desirable physical properties, and the ability to be readily welded. The corrosion resistance is, in general, equal or somewhat superior to that of pure copper; for many solutions they are markedly superior.

There have been some failures of silicon bronze in a steam atmosphere under conditions of stress. There is, however, no evidence indicating that in the absence of stress the silicon bronzes are appreciably attacked by water vapor or steam. At the present time, however, the use of silicon bronzes in steam atmosphere under high stress is not recommended. A study of the effect of steam on stressed silicon bronzes is now being carried out and the data are at present quite incomplete. It is expected that considerable additional information will be available after some of these studies are completed.

Polishing of Copper and Its Alloys for Metallographic Examination

By C. H. Davis*

Location of Test Pieces

Castings—Prepare any section, preferably $\frac{1}{2}$ in. square by $\frac{1}{4}$ in. thick, by polishing the face that is normal to the side of the casting, or in the region of defects. To avoid tearing the cloth on the wheels, bevel the edges of the face of the specimen except where they are to be examined.

(a) In the case of cast copper ingots and wire bars, the uniform practice is to go 1 in. below the "set" and 1 in. in from a side or end. Such points reveal an average distribution of cuprous oxide.

(b) Sections of alloy castings to be subsequently wrought should be taken below the cropping cut at the gate end so as to reveal unsoundness. Shrinkage cavities, cold shuts, and other defects may be searched for at any point, particularly under risers and at heavy sections of sand castings. Complete sections for microscopic examination may be prepared by sawing and grinding, or by finishing the desired surface with a very sharp-pointed tool on a shaper.

Wrought Copper and Copper Alloys—For the estimation of grain size or amount of cold working of sheet metal, polish below and parallel to the surface; though if desired, one may standardize upon a lengthwise section normal to the surface. In the case of rods, wire, tubes, and other drawn material, prepare a longitudinal section either from the center to the very surface, or at points thereon. Transverse sections reveal seams, pipes, and cracks if present.

Manufactured Articles—Examine in such a way as to reveal the grain size and amount of deformation of the original metal and the history of manufacturing operations as fully as possible. For instance, in the case of cartridge shells, prepare a complete longitudinal section from base to rim.

Mounting—When delicate measurements are to be made or the edges of cross sections carefully studied, the specimens are electro-plated with copper or with nickel followed by copper. Thin sections should be mounted singly or in packs in low melting point alloys or in other media, such as plaster of Paris, sulphur, sealing wax, Bakelite, or litharge and glycerine. There is usually a difference in solution pressure between the specimen and the mounting material in certain reagents. Therefore a proper selection must be made, for instance, lead-tin alloys for brasses which are to be etched in ammonia plus H_2O_2 , while Bakelite may be employed for electrolytic etching.

A hydraulic mounting press is convenient for mounting specimens in Bakelite or the clear transparent Pontalite. The low curing temperature makes them excellent mounting media for specimens where higher temperatures would be injurious. Black Bakelite cures at 135°C . under 2500 pounds pressure, also as low as 90°C . at 2500 pounds pressure; Pontalite at 120°C . under 4000 pounds pressure.

Polishing—To obliterate saw marks or to get to the average structural condition below the surface, file the specimen carefully, but omit this operation when the surface only is to be studied. Avoid straining the metal. In the case of hard alloys it is often quicker to use an emery wheel with a copious supply of water. Grades of the finer emery cloths may be employed after filing, though this step is not essential.

The specimen is then applied to the polishing wheels which may be either vertical or horizontal, and move at velocities usually ranging from 1000-1800 r.p.m. though speeds up to 3300 r.p.m. are successfully used. There should be no appreciable vibration, a requirement best met perhaps by having a ball bearing vertical shaft motor for each horizontal wheel. Variable speeds may be secured by the use of a rheostat. Automatic polishing devices and special holders or clamps for specimens may be employed.

In order that the cloths may wear evenly, the specimen is moved constantly from center to edge of the wheel. The position on each wheel is changed so as to polish across the scratches made by the previous operation. On the last wheel a

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rotary motion is given to the specimen to prevent the tailing out of any pits in the metal.

The first polishing wheel is covered with 8-12 oz. canvas duck. The abrasive may be FF Turkish emery, No. 500 carborundum, or powdered alundum. Dripping water keeps the wheel wet. The second wheel is covered with a wool broadcloth and is also kept wet. The abrasive is tripoli. (Two felt covered wheels may be used for the intermediate stage. A good felt retains the emery better than broadcloth. The grades used are first "RF" flour, then "SF 6X" flour emery.) The final wheel may be covered with a fine grade of wool broadcloth, or a selected material of soft nap often known as "kitten's ear". Chamols has also been used. Levigated alumina suspended in water is applied to this final wheel, and the cloth is kept wet with dripping water. Finely powdered magnesia is sometimes used and is applied as a dry powder, but the cloth on which magnesia is used must not be left exposed to the air for long periods because of the formation of carbonate particles. When through, the cloth should be removed from the wheel and kept moist in water containing a little hydrochloric acid. Another polishing powder is jeweler's rouge which may be applied as a thin paste and the wheel just moistened with water.

The specimens are kept wet and thoroughly rinsed free from abrasives between steps. They may be removed wet from the final wheel and immediately etched, or may be dried quickly after an alcohol rinse. When using rouge for the final polish, it is possible to take the specimens from the wheel at the critical moment when the polished face becomes clean and dry. Such a specimen is ready for etching. Pure copper is more difficult to polish than its alloys, especially since a perfect surface is required to detect the presence of cuprous oxide in the unetched specimen.

Generally speaking, an unknown specimen should be examined under the microscope before etching in order to detect flaws, oxides, soft or hard constituents, and insoluble elements, such as lead in brasses. These details may be lost or masked by etching. Variations in the practice of polishing are frequently met with and extreme care is not always necessary to accomplish the desired end.

Reference

Tentative Recommended Practice for Metallographic Testing of Ferrous and Nonferrous Metals (with Bibliography), A.S.T.M. Standard E3-36. 1936, pt. I, p. 773.

Etching of Copper and Its Alloys for Macroscopic and Metallographic Examination

By C. H. Davis*

Etching for Macroscopic Examination—For macroscopic examination the surface may be prepared by grinding and rough polishing or by cutting with a fine tool on a shaper. The chromic acid, ferric chloride, nitric acid, or potassium bichromate reagents as given in the table may be used for etching copper, brass, bronze, copper-nickel-zinc mixtures and other alloys. The specimens may be partially immersed in the solution or the prepared surface may be swabbed with cotton dipped into the reagent. If specimens are porous, drying must be carefully accomplished, using alcohol and at times ether following the water rinse. To preserve the surface temporarily for photographing, the specimen may be covered with a thin film of colorless mineral oil, glycerine, or for permanent preservation, with a thin clear lacquer.

Etching for Microscopic Examination—Forceps having a firm spring and made of nickel-silver or phosphor bronze wire are used to hold all small samples. Platinum tips are silver soldered on these forceps if they are to be used with highly corrosive reagents. The reagent is poured into a watch glass so that the specimen may be easily agitated. A stream of running water should be close at hand. Usually one specimen only is etched at a time, but where many of the same composition and hardness are to be prepared, it is sometimes possible to etch a large number by using a potassium bichromate, ferric chloride, or copper-ammonium chloride reagent, because the action can be closely controlled.

The reagent generally employed in etching copper, alpha brass, and many other copper alloys is ammonia plus hydrogen peroxide. The proportions vary with the copper content. For instance, for pure copper five parts each of ammonium hydroxide (0.88 sp.gr.) and of water, and two parts of 9% (30 volume) hydrogen peroxide; for brass (65% copper), five parts each of ammonium hydroxide and water, and one part of 9% hydrogen peroxide. Pure beta brass may be etched with the last mixture, but alpha plus beta structures are etched first as for yellow brass, then in ferric chloride if one desires to darken the beta. Copper-ammonium chloride may be used in a similar manner, and is especially good for coloring large areas of beta.

A combination of etches must often be used to secure contrasts or the correct coloration of two or more constituents. A beautiful coloration of copper and phosphor bronze can be obtained by following an ammonia-peroxide etching with a few seconds of electrolytic etching. In this case the etched surface must not be swabbed, but should be dried quickly by alcohol, or hot air blast.

The potassium bichromate reagent is not only convenient, but etches alloys of manganese, beryllium, silicon, and other elements with copper that may not be well etched in any other manner. This reagent is also excellent for leaded brass rods, Tobin bronze, pure copper, and the nickel alloys. When beta in brass is to be darkened or a deeper contrast is desired on copper-manganese-silicon or copper-tin alloys, the potassium bichromate etch may be followed by a weak Grard's solution. Copper and beryllium-copper alloys may be first slightly etched in potassium bichromate solution and then placed for 10-15 sec. in the American Brass Co.'s formula, electrolysis solution.

The polish attack method of etching is advocated by many and is widely used. Hudson, Desch, and Pulsifer, among others, have given detailed accounts of procedure with such reagents as ammonia and its compounds.

The time required for etching increases with the amount of annealing received by the material, and decreases with the amount of cold working. The reagents given in the table generally etch well in less than one minute. Some electrolytic etching may require several minutes.

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Hardeners for Copper and Copper Alloys

By Dr. G. H. Clamer*

General—The term "hardeners" is used in the industry to denote alloys employed to simplify introduction of other metals into molten copper or copper alloys; moderate amounts of these added metals do increase the hardness of copper.

Phosphor-Copper—Alloys of phosphorus with copper are manufactured chiefly in two grades containing 10 and 15% of phosphorus respectively. The approximate melting points of these two alloys are 1760 and 1870°F.

The A.S.T.M. Standard Specifications B52-27 for the chemical composition of phosphor-copper state that the material shall conform to the following requirements as to chemical composition:

	Phosphorus Min., %	Phosphorus Plus Copper Min., %	Iron Max., %
Grade A	14.0	99.75	0.15
Grade B	10.0	99.75	0.15

The above chemical compositions are also in accordance with Standard Specifications QQ-C-571 issued by the Federal Specifications Board.

Phosphor-copper may be manufactured by forcing cakes of phosphorus under the surface of molten copper and holding until the reaction ceases, or by the absorption of the phosphorus vapor by the molten copper. The first method is chiefly practiced in this country while the second process is prevalent in foreign countries. All grades of phosphor-copper are furnished as ingots in the form of notched slabs weighing from 15-20 lb. each. The alloys are brittle and can be readily broken in small pieces for weighing purposes. They are also available in shot form.

Phosphor-copper is used in the manufacture of phosphor-bronze and as a deoxidizer for zinc bronzes and other copper alloys.

In phosphor-bronzes, the phosphorus content varies from 0.05 to approximately 1.00%. The effect of phosphorus is to lower the melting point, widen the freezing range, increase shrinkage and fluidity, increase the tensile strength and resistance to compression and lower the pouring temperature of the alloy. It also has a tendency to cause the metal to eat into the sand and cores; therefore, special precautions should be taken to counteract these effects when producing sand castings.

When employed as a deoxidizer, only a small percentage of phosphor-copper is added, the purpose being to introduce only enough phosphorus to insure complete deoxidization of the metal and have no excess phosphorus remaining in the alloy. It is customary to introduce approximately 1 oz. of 15% phosphor-copper for each hundred lb. of metal to perform this function. The addition of phosphor-copper as a deoxidizer is particularly recommended for alloys such as 85-5-5-5†, 88-10-2, high lead alloys, and semi-red brass mixtures containing approximately 10% zinc. Phosphorus is usually considered an impurity in yellow brass but additions of small quantities have been recommended for deoxidizing and cleaning purposes. Not more than 1 oz. of 15% phosphor-copper per hundred lb. of metal should be used for this purpose. An excessive amount of phosphor-copper added to brass alloys containing more than 10% zinc may produce porous castings and cause wrinkle-like formations, often referred to as "spelter marks," on the surface of the castings. Where such conditions prevail, the phosphor-copper additions should be reduced.

Nickel-Copper—The principal alloy of nickel and copper contains approximately 50% nickel and has a melting point of approximately 2350°F. It dissolves readily in brass and bronze mixtures.

Nickel-copper may be produced from electrolytic nickel or from wrought monel metal. There are no standard specifications covering the composition of this prod-

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†Excessive phosphorus in deoxidation of this alloy leads to low ductility. A.S.T.M. Specification B30-36 permits a maximum of 0.03% phosphorus in bronze, red brass, and semi-red brass alloys, and a maximum of 0.01% in yellow brass. Occasionally as much as 0.05% phosphorus is added. The excess above that required for deoxidation is intentionally added to produce fluidity. The excess phosphorus makes it possible to pour a greater number of molds per heat.

uct; however, the approximate composition of the resultant alloys are as follows:

	Made From Electrolytic Nickel, % Min.	Made From Wrought Monel Metal, % Min.
Nickel	50.00	50.00
Iron	0.05	1.20
Carbon	Trace	0.10
Silicon	Trace	0.05
Sulphur	Trace	Trace
Manganese	Trace	0.50
Copper	Balance	Balance

Nickel-copper can be purchased in slabs or small notched ingots weighing approximately 10 lb. each. The slabs or ingots should be thin as the alloy is somewhat difficult to break in small pieces. It can also be purchased in shot form.

Nickel-copper is used in the manufacture of nickel-silver for the addition of relatively small percentages of nickel to the common brasses and bronzes and for the improvement of leaded copper bearing alloys.

In combination with copper and zinc it imparts a white color to the metal and produces a class of alloys known as nickel-silver or German silver. The nickel content of the resultant alloys varies from approximately 5-30%.

There is evidence to support the fact that the addition of 0.50-3.00% of nickel to brass and bronze alloys will result in an increase in tensile strength, yield point, elongation, and resistance to compression, also, that some of these alloys are rendered more fluid and can be poured at lower temperatures despite the fact that the addition of nickel has been found to cause a slight increase in the melting point.

The addition of 0.50 to approximately 1.50% nickel is recommended for brass and bronze castings intended to withstand high internal pressures. Nickel additions cause a reduction in grain size and tend to produce dense, uniform fractures necessary for pressure-tight castings.

The addition of approximately 1.00% of nickel is recommended for high lead copper-base bearing alloys for the purpose of helping to hold the lead in suspension. The presence of nickel increases the rate of cooling to such an extent that the tendency towards lead sweating or segregation is reduced to a minimum.

To insure best results from nickel-copper additions to bronze alloys, special attention to deoxidization may be necessary. For this purpose, a small percentage of phosphor-copper is recommended. 1 oz. of 15% phosphor-copper per 100 lb. of metal should be sufficient to insure complete deoxidization.

Manganese-Copper—This composition is manufactured chiefly in two grades containing 25 and 30% manganese. The approximate melting points of these two alloys are 1700 and 1650°F., respectively.

Manganese-copper is produced by adding metallic manganese made by the aluminothermic process to a bath of molten copper with constant stirring and heating to prevent chilling of the copper. Both grades of manganese-copper are available in the form of ingots or notched slabs weighing approximately 10 lb. each. The slabs or ingots should be thin as the alloys are somewhat difficult to break into small pieces. They are also available in shot form.

There are no standard specifications covering the composition of these alloys; however, the approximate compositions of 25 and 30% manganese-copper produced from the above grade of metallic manganese are as follows:

	25% Grade	30% Grade
Manganese, min. %.....	25.00	30.00
Iron, max. %.....	0.60	0.75
Silicon, max. %.....	0.50	0.60
Aluminum, max. %.....	0.50	0.60
Carbon, max. %.....	0.05	0.05

Manganese-copper finds a major use in the preparation of manganese bronze; in this class of alloys the manganese content varies from 0.25% to approximately 3.50%. There is evidence to support the fact that the addition of manganese increases the tensile strength, yield point, elastic limit and hardness of these alloys with a slight lowering of elongation.

Manganese-copper is also used for deoxidizing brass and white nickel casting alloys containing lead and nickel-silver. There is evidence to show that small

amounts of manganese-copper introduced in alloys similar to 88-10-2 bronze will result in a material increase in tensile strength and elongation. Unlike phosphorus, manganese does not prevent the formation of an oxide skin on the metal during pouring. Manganese also has a tendency to reduce the fluidity of the metal. To counteract these effects, the introduction of a small percentage of phosphor-copper is recommended.

Silicon-Copper—There are various grades of silicon-copper containing from 5-50% silicon. The 10% grade is most generally used for deoxidizing purposes, while the alloy containing 50% silicon is chiefly employed in the production of copper-zinc-silicon bronzes. The melting points of the 10% and 20% grades of silicon-copper are approximately 1500 and 1650°F.

The A.S.T.M. Standard Specification B53-27 for the chemical composition of 10% silicon-copper states that the material shall conform to the following requirements as to chemical composition: Silicon, 10-12; tin, max., 0.25; zinc, max., 0.25; iron, max., 0.75; aluminum, max., 0.25; and copper, remainder. The sum of copper, silicon, and iron shall be not less than 99.4%.

This chemical composition is also in accordance with Standard Specifications QQ-C-581 issued by the Federal Specification Board.

The approximate composition of the 50% grade of silicon-copper is as follows: Silicon, 50; iron, 0.80; aluminum, 0.35; manganese, 0.05; calcium, 0.20; carbon, 0.04; other elements, 0.25; and copper, remainder.

Silicon-copper is manufactured by adding metallic silicon to a bath of molten copper with constant stirring and heating to avoid chilling of the copper. All grades of silicon-copper are available in the form of ingots or notched slabs weighing approximately 10 lb. each. The alloys are brittle and can be readily broken into small pieces for adding to molten baths.

In copper-zinc-silicon bronzes the silicon content varies from 1.00 to approximately 6.00%. The effect of silicon additions in the above amounts is to increase the tensile strength, hardness, and compressive strength in addition to increasing the fluidity of the metal. The presence of silicon also imparts greater corrosion resisting properties to these alloys and renders them admirably suitable for die castings.

Silicon-copper is particularly useful in deoxidizing nonferrous alloys that do not contain lead, such as cast monel metal and nickel-silver, and for the production of pure copper castings. In the presence of lead, the addition of silicon is harmful as it reacts with the lead and produces drossy and dirty castings. Even as little as a few hundredths of 1% produces this difficulty.

Phosphor-Tin—This alloy, used to a limited extent in the production of bronzes, is applied principally to the manufacture of white metals. It is prepared chiefly in two grades containing 3.50 and 5.00% of phosphorus. The 3.50% grade is the one most generally used. The approximate melting points of the two alloys are 925 and 975°F., respectively.

The A.S.T.M. Standard Specification B51-27 for phosphor-tin states that the material shall conform to the following requirements as to chemical composition: Phosphorus, min., 3.50%, and phosphorus plus tin, min., 99.50%.

The above chemical composition is also in accordance with Standard Specification QQ-T-351 issued by the Federal Specification Board.

Phosphor-tin may be manufactured by forcing cakes of phosphorus under the surface of molten tin and holding until the reaction ceases, or by the absorption of phosphorus vapor by the molten tin. It is believed that most of the phosphor-tin produced at the present time is made by the former method. Both grades of phosphor-tin are available in slabs weighing approximately 15 lb. each. Phosphor-tin has a white color and a metallic lustre and is extremely brittle and can be easily broken in small pieces for weighing purposes. It breaks with a coarse crystalline fracture.

As a deoxidizer for babbitt metals, only a small percentage of phosphor-tin is employed, the purpose being to add only enough phosphorus to insure complete deoxidization of the metal and have no excess phosphorus remaining in the alloy. Phosphor-tin can be used to purify babbitt metal which has become oxidized through overheating.

A small amount of phosphor-tin is advantageously added to genuine babbitts containing high percentages of copper for the purpose of increasing the fluidity thus making possible the pouring of thin linings which would otherwise be difficult because of the natural sluggishness of the molten metal.

In tinning operations where the article is dipped into molten tin and it is desirable to obtain thin and uniform coating, small additions of phosphor-tin are recommended.

Phosphor-tin is sometimes used for introducing phosphorus in the manufacture of phosphor-bronze, also for deoxidizing bronze alloys; however, its advantages for such uses do not seem to be evident in view of the fact that phosphor-copper can be used for the same purposes and at a much lower cost.

Brass Foundry Temperature Measurements

By Walter F. Graham*

Necessity for Temperature Control—A number of important advantages accrue in the brass foundry from accurate temperature control of the molten metal by means of pyrometers. First, it is often desirable in a production foundry, where physical properties of the cast metal are not particularly important, to be able to pour a maximum number of molds from a single pot in order to obtain economy of labor. The measurement and adjustment of the starting temperature will assure the foundryman that the last molds poured will contain sound, workable castings and that misruns will be eliminated. Second, the practical operation of the foundry is facilitated, in that the foundry difficulties arising from too high or too low temperature may be minimized. For example, cracks, blowholes and bad surface due to high casting temperatures and misruns, gas inclusions and cold shuts from low temperatures, may be avoided. Third, when the requirements of high strength and ductility are imposed on the foundryman, the maximum physical properties of a given alloy are developed by pouring at as low a temperature as is feasible to run the casting, assuming that the temperature is high enough to enable the liquid metal to feed out sections having a tendency to shrink.

Supplementary benefits obtained from temperature control are reduction in overheating, thereby decreasing the consumption of furnace refractories, and a minimizing of changes in composition due to volatilization of constituents of the alloys.

Pyrometric temperature control will permit the employment of semiskilled labor in handling the metal and a diversified list of alloys can be properly cast.

Effect of Pouring Temperature—High pouring temperatures in general permit excessive grain growth in the alloy during the period of the cooling of the metal in the mold. This lengthened time of cooling also permits undue segregation of impurities in the metal at the grain boundaries. The result is a lowering of the tensile strength and the ductility of the metal which has been poured at a high temperature as contrasted with better physical properties obtained in metal poured at a low temperature. Some patterns are so gated or have such sections that feeding by the pressure head of the metal in order to obtain sound sections demands metal of comparatively high temperature in order to obtain fluidity. This accounts for the belief of some foundrymen that high pouring temperatures are desirable, but it will be obvious that this consideration has nothing to do with obtaining maximum strength in castings of even section by pouring at minimum temperatures.

In obtaining the maximum physical properties it is necessary to work in a temperature range in which small variations bring about considerable effect. Therefore, close temperature control, which can only be obtained by the use of proper pyrometers, is necessary.

Methods of Temperature Measurements—As the use of the molten metal in practically all foundry operations is diversified, as regards the types of castings poured, it is, in practically all cases, necessary to measure the temperature in each individual ladle rather than in the furnace. Furthermore, it is desirable to have the temperature as nearly representative as possible of the temperature of the metal going into the mold. The system adopted may vary for different foundry conditions, but it should in every case be such that it will be flexible, and permit a quick measurement of the temperature of each ladle or crucible immediately before pouring.

In some cases it is desirable to use pyrometer equipment in the form of a portable millivolt meter which can be carried by the operator from pot to pot as the furnaces are emptied. In other cases, particularly where the metal is handled by cranes or monorail systems, it is convenient to have a millivolt meter fastened to the wall or a support adjacent to the line of travel of the ladles. As the whole matter of temperature measurements and their use is based on comparison and judgment it would seem that indicating rather than recording instruments are more adaptable to this service.

Practically all of the alloys handled in the brass foundries give off more or less fume in the ladles and for this reason optical and radiation methods of pyrometry

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are usually of little value. The thermo-electric system, in which there is a millivoltage generated between two dissimilar wires and in which this emf. is measured by a millivolt meter calibrated to a temperature scale, is the method generally used for brass foundry purposes.

The instrument itself should be in the middle range of resistivity as high resistance instruments of high sensitivity are too delicate to use for the rough service which may be expected in the foundry. Low resistance instruments, while rugged in their mechanical construction, are so easily affected in their reading by variations in the external resistance of the line and couplings that they are not particularly well adapted for foundry use. The instrument used should be dead beat, that is, the needle should approach the maximum point slowly without oscillation.

A potentiometer is a desirable instrument to use with the exception that the needle indication is not so easily seen by the operator as in a millivolt meter, and in addition one of the operator's hands is engaged in turning the knob to balance the instrument. The potentiometer has certain advantages over the millivolt meter in that it is not affected by variations in external resistance of the circuits.

The thermocouple or the hot ends of the wires which are immersed in the liquid metal fall into two classes; first, open end, and, second, closed end.

The open end thermocouple consists of two wires of dissimilar alloys of high melting point fastened to a handle. The operator immerses the ends of these wires 4-6 in. in the molten metal until they have each come up to the maximum temperature of the central portion of the metal in the pot. He then withdraws the wires quickly until the tips remain just under the surface of the metal and catches with his eye the maximum reading of the needle of the indicating instrument.

One reason for this manipulation is to avoid the effect of the cooler metal of the surface on the upper portion of the wires, and the reading is supposed to be taken while the tips retain the greater temperature of the metal in the central portion of the pot. The most important reason for raising the tip of an open end couple before taking the reading is to get rid of the film of oxidized metal which covers the surface of the metal between the tips. This film forms instantly after the metal has been skimmed and always has a pronounced but variable effect on the accuracy of the reading. When the tips are raised the film clings to them and is lifted from the surface of the metal with the result that momentarily there is a clear limpid metallic surface between the tips. A reading taken at this time is remarkably accurate. It is evident that this method requires a certain amount of skill in manipulation. It has, however, the advantage of requiring only two unprotected wires which are cheaper in maintenance than fabricated closed end couples. The open end tip gives a very quick reading of the temperature of the metal.

The second method, in which a closed tip is used, involves the use of a couple made by one of a number of methods. The manufacturers of various tips have claims for the advantages obtained by their particular designs, which are outside of this discussion, but in general, the most desirable one is that which gives the quickest reading. The construction of the tip must be such that the junction of the wire is protected from the alloying and corrosive action of the hot metal in order to give maximum life, but protection should be such that there is sufficient heat flow at the junction so that the maximum temperature reading will be obtained as quickly as possible. The closed type of tip may be immersed in the molten metal and the reading taken when the needle of the indicating instrument comes to rest. The construction of this type of couple protects the wires at the surface of the hot metal and prevents the error due to the lower temperature at that point. This couple is easy to manipulate and requires but little skill in handling, but the maintenance cost is higher than for the open end type.

The use of refractory tubing, which gives long life to the inclosed thermocouple, is feasible under certain circumstances where the handling conditions surrounding the use of the couple permit. Practically all nonmetallic protection tubing is fragile and in many cases considerable breakage is encountered in rough foundry usage. Metallic materials for protection tubing are satisfactory, but will eventually corrode at a shorter period than the nonmetallic refractories. Ferrous and nonferrous alloys containing nickel do not give as long life when used for protection tubing as do ferrous alloys containing high chromium.

Standardization of Pouring Temperatures—In a production foundry the pouring temperature for a given pattern can be determined by a study of the fractures and

by gaging the number of misruns obtained. The desirable temperature is the lowest pouring temperature which will give the soundest and toughest metal with the least number of misruns. The effects of small and large gates are obvious and the pouring temperatures decided upon can be raised or lowered or the gating changed in order to obtain the proper results.

After the proper pouring temperatures have been decided upon, the foundryman or pyrometer man can measure the temperatures of the metal going to the particular floor and adjust it by chilling down with gates or scrap castings.

With proper adjustment of gating, generally all patterns of certain type will fall within a given temperature range for castings of equal weight, so it becomes a relatively simple matter to dispatch metal of the proper temperature to the different foundry floors.

In the case of jobbing foundries where relatively large castings are poured, or where molding is done with loose patterns and one or two molds are set up from each pattern, the temperature of the metal is regulated and determined from previous experience with patterns and gating of a similar nature.

The maximum range of temperature encountered for the various alloys in use in the brass foundry is approximately from 1850-2350°F., depending on composition, section, and gating of the casting. The difference between correct and incorrect temperatures for any given alloy or casting may be as small as 20°F. It is obvious that this difference cannot be determined satisfactorily by the eye. The measurement of temperature of molten metal in the brass foundry by pyrometric methods leads to a greater standardization of all the foundry operations, as well as an improvement in the physical properties of the alloys cast.

Hot and Cold Working of Copper Alloys

By R. S. Pratt*

General—Plastic deformation of copper alloys is carried on in a great variety of commercial operations. All of these operations are accomplished by subjecting the material to compressive forces, although the exact nature of the application may vary considerably. The operations may be partially classified as those which are hot working operations and those which are cold working operations.

The hot working operations are those which are performed after preheating the metal to temperatures between approximately 1100°F. and 1650°F. In cold working operations the metal is not preheated above room temperature, although the operation itself may raise the temperature of the metal appreciably. Those copper alloys which are nearly pure copper are quite generally hot worked in the early stages of fabrication. The copper-zinc alloys containing appreciable quantities of the beta solid solution, that is, about 60% copper, are also hot worked commercially. There are other copper alloys which may be hot worked, but most of the commercially hot worked alloys are of the types mentioned above. The copper alloys capable of cold working cover a much wider range of analysis. Practically all of the commercial alloys may be readily cold worked within the limits of the solid solubility of the alloying elements.

In Tables I and II an effort has been made to classify the more common hot and cold working operations with respect to the performance of some of the commercial alloys in these operations. They are intended to cover the more important operations and alloys. The new proprietary alloys and precipitation hardening alloys which are in a rather different class are not covered in these tables.

The ability to either hot or cold work is affected not only by the physical properties of the metal, that is, strength and ductility, but also by the chemical characteristics of the metal and mechanical features of the operation by which the metal is to be worked. It is, therefore, difficult to predict without actual trial, whether or not a given alloy can be successfully worked in any particular operation.

Hot Working—The physical properties of a copper alloy which are required to enable it to be hot worked, are known only generally. Considerable work has been done by various investigators,^{1, 2, 4} to determine the physical properties of alloys at elevated temperatures using different tests for this purpose. The results have not been definitely consistent, particularly when viewed in respect to known results of a commercial hot working practice. Part of this difficulty has been due to the fact that different operations require different properties. Undoubtedly, if it were possible to analyze readily the forces set up in the various operations, a better understanding would be had of the properties required in the alloy. Some of the operations are involved in this respect and as a result the best way in which to determine the hot workability of an alloy in any particular operation is to try it out and learn by experience. Some progress is being made, however, as shown by the fact that many alloys can now be hot worked in operations in which they were scarcely attempted 10 or 15 years ago.

It is a generally conceded fact that the best indications of ability to be hot worked are high ductility and malleability values at high temperatures. Work has been done to determine these properties by both tensile² and compression tests⁴ or drop hammer tests.¹ Tensile strength or deformation under compressive loads as shown by these tests is directly related to the ease with which the alloys can be forged or extruded. Both these values indicate resistance to deformation which is a direct measure of the working pressures required in performing these operations. Increased working pressures mean greater wear on dies and tools, heavier equipment and greater cost. These factors, as well as ability to withstand the operations without failure, have a bearing on the commercial adaptation of the alloy to the operations involved. The success of hot working operations generally seems to depend on a fortunate combination of physical properties with respect to the particular machine in which the operation is to be performed.

One of the primary factors involved in hot working operations is the quantity of impurities in the metal. It is well known that small amounts of lead, bismuth or antimony seriously affect the workability of electrolytic copper. It is also known

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Table I
Classification of Hot Working Operations

Material	Composition				Hot Working Operations					
	Cu	Zn	Pb	Sn	Ni	Extrusion	Stamping	Pressing	Rolling	Piercing
Electrolytic copper.....	99.90	.....	.....	.....	.....	G.	G.	G.	E	E
Gilding metal.....	95.0	5.0	.....	.....	.....	F.	F.	F.	G.	G.
Commercial bronze.....	90.0	10.0	.....	.....	.....	F.	F.	F.	G.	G.
Leaded bronze.....	88.5	10.0	1.5	.....	.....	N.G.	N.G.	N.G.	N.G.	N.G.
Rich low brass.....	85.0	15.0	.....	.....	.....	P.	N.G.	N.G.	F.	F.
Low brass.....	80.0	20.0	.....	.....	.....	N.G.	N.G.	N.G.	F.	F.
Brading brass.....	75.0	25.0	.....	.....	.....	N.G.	N.G.	N.G.	F.	F.
Cartridge brass.....	70.0	30.0	.....	.....	.....	N.G.	N.G.	N.G.	F.	F.
High brass.....	65.0	35.0	.....	.....	.....	F.	N.G.	N.G.	P.	P.
Muntz metal.....	60.0	40.0	.....	.....	.....	E.	E.	E.	E.	E.
Free turn. rod.....	61.0	36.0	3.0	.....	.....	G.	P.	P.	P.	P.
Forging rod.....	60.0	38.0	2.0	.....	.....	E.	E.	E.	N.G.	N.G.
Admir. metal.....	70.0	29.0	.....	1.0	.....	N.G.	N.G.	N.G.	N.G.	N.G.
Naval brass.....	60.0	39.25	.....	0.75	.....	E.	E.	E.	E.	E.
Signal bronze.....	98.75	..	.....	1.25	.....	P.	P.	P.	E.	P.
Phos. bronze.....	96.0	.....	P	4.0	.....	N.G.	N.G.	N.G.	N.G.	N.G.
5.5% phos. bronze.....	94.0	.....	0.15	5.5	.....	N.G.	N.G.	N.G.	N.G.	N.G.
8% phos. bronze.....	92.0	.....	0.15	8.0	.....	N.G.	N.G.	N.G.	N.G.	N.G.
7% nickel silver.....	65.0	28.0	.....	.....	7.0	N.G.	N.G.	N.G.	N.G.	N.G.
18% Ni silver.....	65.0	17.0	.....	.....	18.0	N.G.	N.G.	N.G.	N.G.	N.G.
18% Ni silver.....	55.0	27.0	.....	.....	18.0	N.G.	N.G.	N.G.	N.G.	N.G.
8% Al bronze.....	92.0	.....	Al	.....	.....	G.	G.	G.	G.	G.
20% cupro-Ni.....	80.0	.....	8.0	.....	20.0	F	P.	P.	G.	N.G.

E.—Excellent—Readily worked to great extent without special equipment.
G.—Good—Readily worked but requires high class equipment and control
F.—Fair—Requires special equipment and (or) workable to limited extent.
P.—Poor—Can be worked only with difficulty.
N. G.—Not commercial operation.

E.—Excellent—Readily worked to great extent without special equipment.

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P.—Poor—Can be worked only with difficulty.

N.G.—Not commercial operation.

Table II
Classification of Cold Working Operations

Material	Composition				Cold Working Operations							
	Copper	Zinc	Lead	Tin	Nickel	Rolling	Wire	Drawing Tube	Shell	Cupping	Heading	Machining
Electrolytic copper.....	99.90	.....	.....	.....	.....	E.	E.	E.	G.	G.	E.	F.
Oxygen free copper.....	99.90	.....	.....	.....	.....	E.	E.	E.	G.	G.	E.	P.
Gliding metal.....	95.0	5.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	P.
Commercial bronze.....	90.0	10.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	F.
Leaded bronze.....	88.5	10.0	1.5	.....	.....	F.	F.	P.	P.	N.G.	F.	E.
Rich low brass.....	85.0	15.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	F.
Low brass.....	80.0	20.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	P.
Brading brass.....	75.0	25.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	P.
Cartridge brass.....	70.0	30.0	.....	.....	.....	E.	F.	E.	E.	E.	E.	F.
High brass.....	66.0	34.0	.....	.....	.....	E.	E.	E.	E.	E.	E.	F.
Leaded high brass.....	66.0	33.0	0.7	.....	.....	G.	G.	G.	G.	G.	G.	P.
Muntz metal.....	60.0	40.0	.....	.....	.....	P.	G.	P.	P.	P.	N.G.	E.
Free turning rod.....	61.0	36.0	3.0	.....	.....	G.	P.	P.	P.	N.G.	F.	E.
Forging rod.....	60.0	38.0	2.0	.....	.....	E.	E.	E.	E.	E.	E.	P.
Admiralty metal.....	70.0	29.0	.....	1.0	.....	G.	E.	E.	E.	E.	E.	P.
Naval brass.....	60.0	39.25	.....	0.75	.....	G.	G.	G.	G.	F.	E.	P.
Signal bronze.....	98.75	.....	.....	1.25	.....	E.	E.	G.	G.	G.	E.	P.
Phosphor bronze.....	96.0	.....	Phos.	4.0	.....	G.	G.	G.	G.	G.	G.	P.
0.15% phosphor bronze.....	94.5	.....	0.15	5.5	.....	G.	G.	G.	G.	G.	F.	P.
5.5% phosphor bronze.....	92.0	.....	0.15	8.0	.....	G.	G.	G.	G.	G.	F.	P.
7% phosphor bronze.....	65.0	28.0	.....	.....	7.0	G.	G.	G.	G.	G.	G.	P.
18% nickel silver.....	65.0	17.0	.....	.....	18.0	G.	G.	G.	G.	G.	G.	P.
18% nickel silver.....	55.0	27.0	.....	.....	18.0	G.	G.	G.	G.	G.	G.	G.
8% aluminum bronze.....	92.0	.....	Al	.....	.....	F.	F.	F.	F.	P.	F.	P.
20% cupro-nickel.....	80.0	8.0	20.0	G.	G.	G.	G.	G.	G.	P.

E.—Excellent—Readily worked to great extent without special equipment.
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N.G.—Not commercial operation.

that smaller quantities of at least some of these elements affect the hot working of the copper alloys, but there is little quantitative evidence to support the known results experienced. Tests by Bunting⁴ on brass give some data on the effect of lead and tin. The quantitative effect of the tin and lead brought out by the type of test used are not significant. In the alpha copper-zinc alloys, lead seems to develop intercrystalline weaknesses which cause some cracking. In the drop hammer test this is only shown by observation of the surface of the compressed cylinder.

In the copper-zinc alloys, hot working has generally been associated with alloys which at the higher temperatures consist largely of the beta constituent. Copper also is readily hot workable and some of the alloys containing 10% of zinc or less, have also been hot worked for some time. It is only in the last few years, however, that any appreciable amount of commercial hot working has been done on the alloys from 10-30% zinc. Undoubtedly much of the progress along this line has been made possible by the reduction in amount of lead, usually found as an impurity in the zinc. Probably the apparent hot shortness of high brass has been due to 0.04-0.05% of lead, which most of these alloys formerly contained.

A similar advancement in copper-tin alloys has been noted in the past few years, although probably for a different reason. A few years ago alloys containing more than 2% of tin were not considered hot workable. Some concerns are now hot rolling copper-tin alloys containing as much as 4% tin, although as far as is known, no other hot working operations have been successful. The advances in this alloy have been due to improvements in heating and rolling technique, rather than improvement in the purity of the alloy.

Certain of the nickel-silver alloys with copper contents of about 50% may be hot worked as well as cold worked. A paper by Price and Grant⁵ shows the range of analysis on which both hot and cold working operations may be employed. Most of the commercial alloys, however, are not readily hot worked.

Cold Working—Due to the greater amount of experience available considerably more is known about the possibilities of cold working copper alloys. As in the case of hot working, however, there is no conclusive laboratory test which is capable of predicting the action of any given alloy in all types of cold working operations. As in hot working, this is due primarily to the complicated forces to which the metal is subjected. While in general the metal is caused to flow by compressive forces, in most cases there are additional tensile forces set up locally which may cause failure.

Generally speaking, the material to be successfully cold worked must show in physical tests at room temperatures an appreciable elongation and reduction of area. Most commercial wrought copper alloys show good elongation and reduction in area test values in the annealed condition. Certainly if test values are less than about 25% elongation in 2 in. and 50% reduction in area, difficulty will be encountered in performing any appreciable amount of cold working, even of the most simple kind, such as rolling and wire drawing. Roughly the extent of drawing possible in one operation depends on the amount of elongation in the tensile test. The extent to which an alloy may be redrawn seems to vary with the reduction of area and more particularly with the degree to which the reduction of area value is reduced by each successive draw.

Despite the fact that cold working operations are compressive operations, little work has been done as yet to correlate the characteristics of laboratory compression tests to commercial operations. Laboratory compression tests are not conveniently made to give as much information of a quantitative nature as the tensile test, because of the difficulty in making them without stresses other than compression of indeterminate types and amounts. Within the past few years, however, considerable time has been spent by investigators in this connection,⁶ with particular reference to the sheet metal cupping problems.⁷ Some progress has been made but as yet there has been no unanimity of opinion as to the results obtained.

What has been said up to this point applies only to the alloy itself in its internal characteristics. Quite often these properties are normal and satisfactory, but because of surface conditions, which are of course related to the alloy, difficulties arise in cold working. The oxides of copper and zinc formed in the annealing operation cause trouble, but are readily dissolved and removed from the surface of the copper-zinc alloys by dilute sulphuric acid. In the alloys containing tin, nickel,

or silicon, the oxides formed are not so readily removed and will, unless other precautions are taken, give difficulty in commercial cold working. For many years the nickel bearing alloys have been bright or clean annealed in some way, to avoid this difficulty. With the increasing use of tin and silicon alloys similar steps will probably be found of help.

There are also many cases in which the type of lubricant used has been found to be important in the success of cold working operations. The purpose of a lubricant is to provide a film between the metal surface and the die or tool surface. A lubricant must be used which protects the surface and which even at high pressures will not permit the alloy and the die or tools to come into contact. The surface of the alloy must also be such as to hold the lubricant and not be either so smooth as to fail to hold it, or so rough as to produce stress raisers on the surface.

Impurities in the alloy are also the cause of difficulty in cold working. Of the common impurities lead and iron tend to reduce the ductility of the alloy as compared with the purer alloys. Iron raises the strength of the alloy and reduces the normal grain size produced by annealing after cold working. If these materials are present, it becomes more difficult to cold work. However, other advantages such as increased tensile strength and hardness may be obtained. Impurities such as tin have only a slight effect on the cold working of the alloy, although when present as an ingredient, it appreciably increases the strength of the alloy. Antimony and bismuth result in severe cold shortness, when present in quantities of as much as 0.01%.

Machining—As with all metals, machining operations are actually cold working operations, involving the shearing of small sections from the surface of the metal. The commercial success of this operation depends on the physical characteristics of the material to a large extent. The strength of the material affects the stress to which the cutting edge is subjected and the ductility affects the type of chip formed and the ease with which it is removed. The method of lubrication and design of tools are also important factors and they must be varied in accordance with the properties of the alloy. A small amount of lead added to the copper alloys greatly increases their machinability. The improvement is brought about by the lesser ductility of the leaded alloy. This in turn results in the chips breaking up as they leave the tool, reducing the wear on the tool and permitting the rapid removal of the chip. Alloys for machining purposes, therefore, normally contain some lead. The other alloys can be machined, but the speed and extent of the commercial operation is considerably reduced.

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Machining of Copper Alloys

D. K. Crampton* and H. P. Croft†

The machining of wrought copper alloys containing over 50% copper can usually be effected by machines and tools designed for the cutting of ferrous metals, but free cutting nonferrous alloys such as the leaded brasses may be machined more rapidly than cast iron or steel and some changes in tool angles and lubricants are beneficial.

For the purpose of discussing the machining of copper alloys they may be divided roughly into the following classes.

Class I. Free or semifree cutting brasses to which some element has been added specifically to improve cutting qualities.

Class II. The straight brasses without any such additional element. These are seldom machined by the consumer to any considerable extent but present cutting problems to the producer.

Class III. The refractory bronzes, high in copper content, and containing one or more additional elements which impart high strength, hardness and toughness.

Class IV. The refractory alloys of Class III to which a moderate amount of another element has been added specifically to improve the machining properties.

Class V. Copper. Due to combination of toughness and low hardness the conditions for machining copper often differ from those suitable for Class III.

Machinability is a term not readily defined, but usually described by its effect on cutting properties and conditions of operation. Insofar as wrought copper alloys

are concerned, it is more dependent on composition than on physical or other mechanical properties. The metal being machined must, of course, be rigid enough to stand up against the turning tool without distortion. The temper of wrought copper alloys for automatic screw machining should, accordingly, be hard, consistent with ability to withstand any other possible subsequent cold working operation such as upsetting, flanging or bending. A softer temper is conducive to more rapid drilling. Generally speaking, machinability improves considerably with increasing amounts of lead and decreases with increasing amounts of tin, silicon, aluminum, nickel, and other elements.

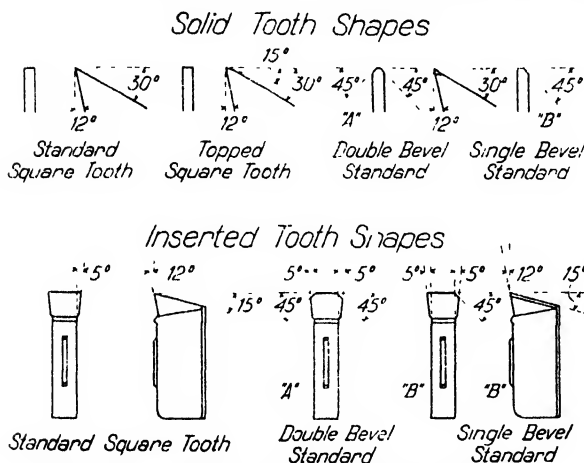


Fig. 1—Solid and insert tooth shapes for circular saws

It also varies with the amount of copper present, the maximum machinability in the straight brasses being attained between 56 and 63%.

Machining operations should be carried out in such a manner as to produce the part in question for the lowest over-all cost and the conditions for accomplishing this might not be those which would produce the lowest power consumption, least pressure on tool, lowest temperature generated at the tool point or other criteria by which the efficiency of machining operations are often rated. Tool manufacturers' publications have a tendency to specify operating conditions which will give long if not maximum tool life whereas economical production might often be furthered by exceeding these conditions at the expense of the tool.

Tool Angles—Clearances of 4-10° are used with copper alloys while top or back rake angles range from 0-30° depending upon the alloy. Classes III and IV should be machined with greater clearance and rake angles than Class I.

Speeds—It is customary to run free cutting brass rod at the maximum spindle speed of the screw machine. However, surface speed does not always depend upon

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Diameter of Stock, in.	T Thickness, in. *	D Depth of Angle for Brass (Class I)
$\frac{1}{16}$	0.020	0.0085
$\frac{3}{16}$	0.030	0.013
$\frac{1}{8}$	0.040	0.017
$\frac{5}{16}$	0.050	0.0215
$\frac{3}{8}$	0.060	0.0255
$\frac{7}{16}$	0.070	0.030
$\frac{1}{2}$	0.080	0.034
$\frac{5}{8}$	0.090	0.038
$\frac{3}{4}$	0.100	0.042
$\frac{7}{8}$	0.120	0.051
$1\frac{1}{8}$	0.140	0.059
$1\frac{1}{4}$	0.160	0.068
$1\frac{3}{8}$	0.190	0.081
$2-2\frac{1}{2}$	0.220	0.093
For tools $\frac{3}{4}$ - $\frac{1}{2}$ incl		Feed—0.0035 in.

Form Tools—Circular

	I	II	Class III	IV	V
Top or back rake, degrees..	0	5-7.5	10	..	15
For tools $\frac{1}{2}$ -1 in.....	Feed {Rough 0.0015-0.004 in. Finish 0.001-0.002 in.}				

Hollow Mills and Balance Turning—Class I—The top or back rake is equal to zero for brass, and the top or face of the teeth is parallel with the center line to avoid "hogging in." The clearance is 12-15°, cutting edges parallel to radii, but for brass the teeth should be ahead of the center lines 0.010-0.015 in. because subsequent grinding of the teeth will move the cutting edge back toward the center line which after passing, the cutting action would be impaired.

Turned dia in	Width of Cut, in.	Feed, in.
Under $\frac{1}{2}$	$\frac{1}{16}$	0.012-0.030
	$\frac{3}{16}$	0.010-0.025
	$\frac{1}{4}$	0.010-0.025
Pointing and Facing Tools.....		0.001-0.0025
Recessing Tools, end cut		0.001-0.005
Inside Cut $\frac{1}{4}$ -1 in		0.0025-0.008

Skiving Tools—For Class I the face of the tool block below the cutting edge is ground back 10-12° for clearance.

Swing Tools—These are not perpendicular but inclined about 12° toward the work. For brass, Class I, the top face is ground 12° so as to make it horizontal. For Class III and IV the angle should be slightly greater. To improve the finish on Class I metals. raise cutting edge slightly above arc through the center.

	Width of Cut, in.	Feed, in.
Forming	$1\frac{1}{2}$ - $\frac{1}{4}$	0.0012-0.002
	$\frac{3}{4}$ - $\frac{1}{2}$	0.0008-0.001
	$\frac{1}{2}$	0.008
	$\frac{3}{8}$	0.006
Turning Straight.....	$\frac{1}{4}$	0.005
	$\frac{1}{8}$	0.004

Drilling

	I	II	Class III	IV	V
Helix angle, degrees.....	20-40*	30	....	....	40
Clearance angle, degrees.....	12-15	....	....	10-12	....
Web to edge angle, degrees.....	135	140	....	....	140
Included point angle, degrees.....	118	....	....	....	100
Speed ft. per min. for depths up to 10 × dia....	350-700	....	....	....	200
For small diameters (under .080 in.).....	250-350	150	70-180	....	100-125
Lubricant	Dry or Paraffin Oil	....	....	....	Soda Water

*For quick chip removal, but tends to "pull" in to work.

	Hole Dia., in.	Feed, in.	
		Deep Holes	Shallow Holes
	0.020		0.0015
	0.040		0.002
	★		0.004
	★	0.005	0.012
	★	0.005	0.015
	★	0.010	0.020
	1/4	0.010	0.014
	1/4	0.010	0.016
	1/4	0.010	0.016
	1/4	0.010	0.016
	1/4	0.010	0.016
Center drills under.....	1/4		0.003
over... ..	1/4		0.006

Heavier than
for steel to
eject chips.
Feed also de-
pends on wall
thickness.

or over, actually
limited by chuck-
ing capacity.

Reamers	Depth of Cut, in.	Hole Dia., in.	Feed, in.	Clearance
	0.003-0.004	Under 1/4	0.010-0.007	7-8°
	0.004-0.008	Over 1/4	0.010	....

Speeds—Class I. Same as for drilling.

Drills—metal blasted flutes for brass {
buffed flutes for copper} to assist chip ejection.

Deep Holes—use decreasing helix

—use two straight flutes

—rotate drills opposite to work to remove chips and obtain greater cutting speeds.

—drill to depth = 5 × dia., then remove drill and finish with second operation.

—half round drills reduce time 50%—start hole to 2–3 × dia. with usual twist drill to center properly.

To use heavy feeds without pulling drill into work, grind off cutting edge angles, that is reduce rake at the cutting edge.

Thread Cutting Chasers-Tangent

	Class				
	I	II	III	IV	V
Rake angle, degrees	-5 to +10	10-20	10-30		28-35
	(Second figures for use when helix built into chasers)				
Chasers, tap and die					
Hook angle, degrees.....	-7 to +7	4	7-10	7	10-25
Chasers, circular					
Face angle, degrees.....	0	1	15	..	2
Hook angle, degrees....	5	5	20		25
Clearance angle, degrees... ..	12	12	12	12	12
Above angles vary with exact composition, machine and condition, speed, lubricant, and length of throat					
Taps for brass—commercial are satisfactory.					
Speeds—multiple spindle machines 1/4-1/2 machine speed					

Knurling and Thread Rolling—These operations are grouped together as they consist essentially of displacing metal under pressure by an indenting tool thereby differing from strictly cutting operations. Due to this inherent difference the highly leaded and consequently brittle (in shear) brasses are less suited than the semileaded or nonleaded alloys. However, it is possible to supply standard free turning brass rod in a lighter temper than "drill" which will permit the majority of thread rolling and knurling operations and still provide excellent machinability for strictly cutting operations. This temper is known as "quarter hard."

For the most severe knurling and thread rolling operations semileaded or nonleaded alloys should be used. Coarse knurls must be effected at a slower speed than fine knurls.

Knurl Tools	Class I	
	Feed, in.	
Turret on	0.025	
off	0.050 up	
Side or swing	0.007-0.012	
Top	0.007-0.014	

For thread rolling of high brasses the blank should be turned to approximately (– 0.002 in.) the pitch diameter. The blank diameter should not vary more than 0.001 in.

Sawing—Circular Saws

Form and Size	Alloy Class	Grade Steel ^a	Tooth Type	Dia. in.	Thickness, in.	No. Teeth	Hook Angle ^a	Rim Speed, Ft. per Min.	Feed, In. per Min.	Lubricant ^c	Rockwell C Hardness per side	Chromium Plated .002 in. Taper per in.	Hollow Ground
Sheet, ½-1"	1,2,4 3,5	S.H.S.S. H.S.S.	S.S.T. Ins.B.S.T."A"	12 12	¼ ⅜	70-80 28-32	0-5 5-10	1500 2500	10-20 10-20	Sol. Oil	52-56 60-62	Yes No	0.0035 0.0010
Rod, up to 1½"	1,2,4 5	S.H.S.S. S.H.S.S.	S.S.T. T.S.T.	12 12	⅜ ⅝	150-200 100-125	10-15 10-15	4-5000 4-5000	60 30	Grease stick Grease stick	52-56 52-56	Yes Yes	0.0035 0.0035
Rod, 1½-4"	3 1,2,4	H.S.S. H.S.S.	Ins.S.S.T. Ins.Alt.S.S.T. &B.S.T."A"	12 16	⅝ ⅞	75-100 60-64	5-10 10-15	2-3000 1000	20-30 30-40	Grease stick Compound	60-62 64-68	No No	0.0010 0.0035
Rod, 4-8"	5 3	H.S.S. H.S.S.	" "	16 28	⅞ 1	60-64 60-80	10-15 10-15	1000 750	20-30 10-20	Compound Compound	62-64 64-66	No No	0.0010 0.0010
Tubing, dia. up to 1"; wall thickness up to .050"	1,2,4,5 3	H.S.S. H.S.S.	S.S.T. S.S.T.	10 10	⅞ 1	60-80 60-80	10-15 5-10	6-750 5-650	15-25 10-15	Compound Compound	62-64 62-64	No No	0.0010 0.0010
Tubing, dia. up to 1"; wall 0.050-0.250"	1,2,4,5 3	H.S.S. H.S.S.	S.S.T. S.S.T.	10 10	⅞ 1	180-200 180-200	10-15 10-15	5-6000 5-6000	100-200 50-100	None Grease stick	60-62 57-61	Yes Yes	0.0035 0.0035
Tubing, dia. 1-3"; wall up to .100"	1,2,4,5 3	S.H.S.S. H.S.S.	S.S.T. Ins.S.S.T.	12 12	⅞ 1	110-120 90-100	10-15 5-10	4-5000 3-4000	75-100 25-75	Grease stick Grease stick	52-56 62-64	Yes No	0.0025 0.0025
Tubing, dia. 1-3"; wall .100-.250"	1,2,4,5 3	S.H.S.S. H.S.S.	S.S.T. Ins.S.S.T.	12 12-16	⅞ 1	110-120 110-120	10-15 5-10	4-5000 3-4000	50-100 25-75	Grease stick G.S. & Compound	52-56 62-64	Yes No	0.0025 0.0025
Tubing, dia. over 3"; wall over ¼"	1,2,4 5 3	H.S.S. H.S.S. H.S.S.	Ins.Alt.S.S.T. &B.S.T."A" "	16 & over 16 & over 16 & over	⅞-⅞ ⅞-⅞ ⅞-⅞	3-4 per in. dia. 3-4 per in. dia. 3-4 per in. dia.	10-15 10-15 5-10	2-3000 2-3000 1-2000	25-75 25-50 10-20	Compound Compound Compound	64-66 64-66 62-64	No No No	0.0010 0.0010 0.0010

^aS H.S.S. is a trade designation for semihigh speed steel saw and H.S.S. for high speed steel saw.^bSee Fig. 1 for tooth types.^cCompound made up as water emulsion of soluble oil. Use 10% oil by volume and 1 lb. heavy soap per 20 gallons compound.

Table I
Machinability

Trade Name	Composition, %				Tensile Strength 1000 Psi. 1000 Psi. in 2 in.	Yield Point 1000 Psi. in 2 in.	Rockwell		Relative Surface Machinability Speeds, (Free Cutting ft. per Brass = 100)		Cold Heading Properties		Class
	Copper	Lead	Tin	Zinc			F	B			Cold Heading Properties	Cold Bending Properties	
Muntz Metal	60	....	....	40	50-65	25-55	95-110	68-94	30	150	Good	Good	II
Forging Rod	60	2	....	38	50-65	25-55	95-110	68-94	80	400	Poor	Fair	I
Free Turning Rod	62	3	5	34	45-65	25-55	90-105	58-82	100	500	Poor	Fair	I
High Brass Rivet Wire	65-70	....	....	Bal.	45-65	25-50	90-105	58-82	30	150	Excellent	Excellent	II
High Brass Pipe	66	0.5	....	33.5	45-65	25-50	90-105	58-82	60	300	Good	Good	I
Semileded Rod	65	1	....	34	45-65	25-50	90-105	58-82	70	350	Fair	Good	I
Free Cutting Brass Pipe	65.5	1.75	....	Bal.	45-65	25-50	90-105	58-82	80	400	Poor	Fair	I
Naval Brass (Chamet or Tobin Bronze)	60	....	0.75	Bal.	55-70	25-55	95-110	68-94	30	150	Good	Good	II
Leaded Naval Brass (Leaded Chamet Bronze)	60	1.5	0.75	Bal.	55-70	25-55	95-110	68-94	70	350	Fair	Fair	I
Red Brass	85	....	....	15	45-65	25-45	80-100	40-75	30	150	Excellent	Excellent	II
Hardware Bronze	84	1.75	....	Bal.	45-65	25-45	80-100	40-75	80	375	Fair	Good	IV
Commercial Bronze	90	..	....	10	40-60	30-40	75-95	31-70	20	100	Excellent	Excellent	III
Leaded Commercial Bronze	89	2	....	9	40-60	30-40	75-95	31-70	90	450	Fair	Good	IV
444 Bronze	88	4	4	4	45-65	35-45	80-100	40-75	100	500	Poor	Poor	IV
Copper	100	....	....	..	35-50	25-40	70-80	23-40	20	125	Excellent	Excellent	V
Leaded Copper	99	1	....	..	35-50	25-40	70-80	23-40	80	375	Good	Good	IV
Phosphor Bronze	95	....	5	..	55-83	30-60	95-115	68-100	20	100	Good	Excellent	III
Leaded Phosphor Bronze	94	1	5	..	55-83	30-60	95-115	68-100	50	250	Fair	Good	IV
Age Hardening Nickel Aluminum Bronze	91	....	7.5	1.5	55-100	25-80	75-110	40-92	20	100	Excellent	Excellent	III
Silicon Bronze (Olympic, Duronze, Everdur, Herculey)*	96	....	3	1	55-100	25-80	75-110	40-92	30	150	Excellent	Excellent	III
Leaded Silicon Bronze (Free Cutting Olympic, Everdur, and Herculey*)	95.5	0.5	3	1	55-100	25-80	75-110	40-92	60	300	Good	Good	IV

*There are many other silicon bronzes available, some the subject of United States patents. The more common structural silicon bronzes contain about 3% silicon, which largely determines most physical properties of this type alloy. Instead of zinc these contain small percentages of manganese, tin, or combinations of these elements.

Physical properties depend considerably on form, size, temper draw and temperature of last anneal. The above values are for the range from soft annealed to drill temper, that is, finished with a temper draw of 15-25% reduction in area. Heavier reductions result in higher tensile strengths, yield points and hardness figures with lower elongations.

Milling—Many variables enter into milling practice but in general conditions are determined by the finish desired. The high tooth of the cutter will always leave a series of parallel ridges. For finish cuts the following conditions hold:

	I	II	Class III	IV	V
Rake angle, degrees.....	0-10	..	0-10	....	10-15
Clearance angle, cutters over 3 in. dia....	10-12	....	4-12	....	12-17
cutters under 3 in. dia....	6-7.5	....	3-6	....	8-9
Feed, ft. per min.....	1-2	....	1-2	....	.....
Speed, ft. per min.*.....	150-200	....	60-200	....	100-200
Depth of cut may vary between wide limits.	.010-.250				
For very rough cuts on heavy slabs—					
cutters 6 in. dia.....					
Rake angle, degrees.....	0	0	0	0	
Clearance angle, degrees.....	8-12	8-12	8-12	8-12	
Feed, ft. per min.....	15-20	15-20	10-12	15-20	
Speed, ft. per min.....	1100	1100	1100	1100	
*Actually governed by finish desired.					
At high speeds the greater the helix and the feed, the greater should be the clearance.					
Use of a coolant is recommended.					
Engraving tools—Class I—dia. under $\frac{3}{8}$ in.—surface speed of 400 ft. per min.					

Band Saws

Type	II	Class III	IV	V
	Alternate left and right	Wavy	Alternate	Alternate
Teeth per in.	10	18	14	10-12
Speed, ft. per min....	300	250	....	....
Feed, in. per min.....	3	2	....	....

Grinding

Material and Job	Abrasive	Grain	Grade	Bond
Brass, Class I and II, and bronze, Class IV				
Cylindrical	Silicon carbide	36-60	Med. Hard	Vitrified
Internal	" "	36-60	Med.	Vitrified
Surfacing, Cups and				
Cylinders	" "	24-36	Soft	Vitrified
Snagging	" "	20-36	Hard	Vitrified
Cutting Off	" "	24-36	Hard	Resinoid and rubber
Bronze, Class III				
Cylindrical	Aluminum oxide	36-60	Med. Hard	Vitrified
Internal	" "	40-60	Med. Hard	Vitrified
Snagging	" "	20-30	Hard	Vitrified
Cutting Off	" "	24-36	Med. Hard	Resinoid and rubber
Copper, Class V				
Surfacing, Cups and				
Cylinders	Silicon carbide	14-20	Soft	Vitrified
Cutting Off	" "	24-36	Hard	Rubber
Coolant, 5% soda solution or clear soluble oil.				

Machinability—The relative machinabilities listed in Table I are only approximate and are based on free cutting brass rod, drill temper taken as a standard of 100. The machinabilities indicate approximately the average comparative performance which may be expected in the various operations of turning, drilling, milling, sawing, and grinding.

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Data received from: A. C. Spark Plug Co., Brown & Sharpe Mfg. Co., Carborundum Co., Caterpillar Tractor Co., Cincinnati Milling Machine Co., Cleveland Twist Drill Co., Davenport Machine Tool Co., Dill Mfg. Co., Harris Calorific Co., Lukenheimer Co., National Acme Co., Norton Co., Vanadium Alloys Steel Co., Waterbury Mfg. Co.

Spinning of Copper and Copper Alloys

By L. A. Ward*

Spinning of copper is particularly adapted to the manufacture of relatively small quantities of any given article since the necessary tools are relatively cheap when compared to those used in draw or stamp presses. Hence, trophy cups, vases, and models are frequently produced by spinning. It is also used for quantity production of articles where this method is more economical than others.

In addition to copper, there are a number of copper-base alloys which are used for spinning. These include gilding metal, commercial bronze, red brass, high brass, and nickel silver. The choice of alloy will usually depend on the color desired, but frequently the choice is also influenced by physical properties, cost, or both. The most commonly used nickel silver is the 18% nickel alloy. The most commonly used copper is electrolytic or tough pitch copper, but for some applications phosphorus deoxidized copper has been found superior while for others oxygen-free high conductivity copper has certain inherent advantages.

Nominal analyses and average physical properties of copper and copper-base alloys in the temper usually used for spinning are as follows:

Alloy	% Copper	% Zinc	% Nickel	Tensile Strength, psi.	% Elongation in 2 in.	Grain Size, mm.	Rockwell "F" Hardness
Copper	100*			32,000	45	0.030	40
Gilding metal	95	5		36,000	44	0.030	50
Commercial bronze	90	10		38,000	45	0.030	53
Red brass	85	15		42,000	47	0.030	60
Nickel silver (18%)	65	17	18	57,000	40	0.040	85
High brass	70	30		50,000	60	0.035	65

Note—The above physical properties are based on sheet 0.040 in. thick.

*Phosphorus-copper contains approximately 0.02% phosphorus.

Certain classes of articles can best be spun from special tempers.

The equipment consists of a lathe, spinning chucks, and tools. The head stock should provide speeds of 1200, 1800 and 2400 r.p.m. The lower speeds are used for large articles or thick sheets while the higher speeds are used for small articles, thin sheets, and for finishing operations such as planishing.

The chucks may be made of wood, cast iron, or steel, depending on the number of pieces to be made. Because of the high pressure used in spinning, a hardened steel chuck will last much longer and be more satisfactory for quantity production and will also aid in producing a smoother surface. Where the inside surface of a spun article is to be polished, a hardened steel chuck will be found much more satisfactory.

The number of chucks necessary depends on the shape of the article to be produced and the ratio of the depth and diameter of the finished shell to the diameter of the original circle. Articles of which the side walls are perpendicular to the base are much more difficult to spin than those with sloping walls and will normally require a greater number of chucks.

Special sectional chucks are used where the mouth of the finished shell is smaller than the main body so that the chuck may be drawn from the shell after the spinning operation. At times offset rolls are used in place of sectional chucks. The advantage of this method is that the chuck does not have to be taken off for every article and thus it is possible to increase the speed of production. This method is most frequently used in conjunction with draw-press-forming of articles and is economical only for large quantity production.

The spinning tools used are usually made from carbon steel (1.1% carbon), but may be made from special alloy steel or have a special hard alloy tip. The tools are usually made from $\frac{1}{4}$ in. rod and the ends have varying shapes depending on the use such as forming, planishing, or curling. The tool itself is about 18 in. long and fitted into a wood handle of approximately the same length. Yellow laundry soap is generally used as a lubricant although heavy oil or grease is sometimes used.

The amount of reduction possible without annealing will vary considerably with

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the alloy, the shape of the part and the size and thickness of the blank. When heavy blanks are being spun it is impossible to give heavy reduction due to the amount of pressure necessary. Again, with thin blanks wrinkling is much more severe and troublesome on heavy reductions. Consequently, in practice, the operator is the best judge of when it is necessary to stop the operation and anneal.

Annealing should be carried out at approximately 1000°F. and is preferably done in a furnace designed for annealing copper and copper alloys. If necessary, it can be done with a blow torch, but it is much more difficult to uniformly soften an article this way, and whenever possible such a method should be avoided. After annealing, the article must be cleaned to remove the oxide or scale and this is done in a 10-15% sulphuric acid solution, usually warm, followed by rinsing in cold and hot water.

The flow of copper and copper-base alloys during spinning is regulated in the same manner as for any other metal and buckling is avoided by holding a flange on the blank during spinning. No definite rule can be given for the width of this flange, but excessive thinning will be encountered if the flange is too wide, while buckling will occur if the flange is allowed to become too narrow. There will always be some thinning during spinning and where a definite wall thickness is desired this must be taken into account.

Although mass production of copper articles is now usually carried out in presses, the art of spinning copper alloys is still practiced extensively.

Constitution of Gold Alloys and Properties

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The Constitution of Gold-Copper Alloys

By Dr. Oscar E. Harder*

The early use of alloys of gold with copper in the form of coins and ornaments naturally made this system one of the first to which the various scientific methods for the study of alloy systems were applied as they were introduced. Strangely enough, the true nature of these alloys was not discovered until about 1916, and even today there is still lacking complete information regarding the crystal structures of alloys of different compositions and after different thermal treatments, although the alloys of gold and copper have been the subject of numerous X-ray investigations during the past decade.

The discovery that gold-copper alloys of certain compositions respond to heat treatment has created unusual interest in this system, because the mechanism of hardening is by atomic rearrangement and does not involve the precipitation phenomenon. The practical application of heat treating alloys containing gold and copper in considerable proportions to produce tough and ductile or hard and strong products by simple processes has been of great interest to the dental, jewelry and other professions.

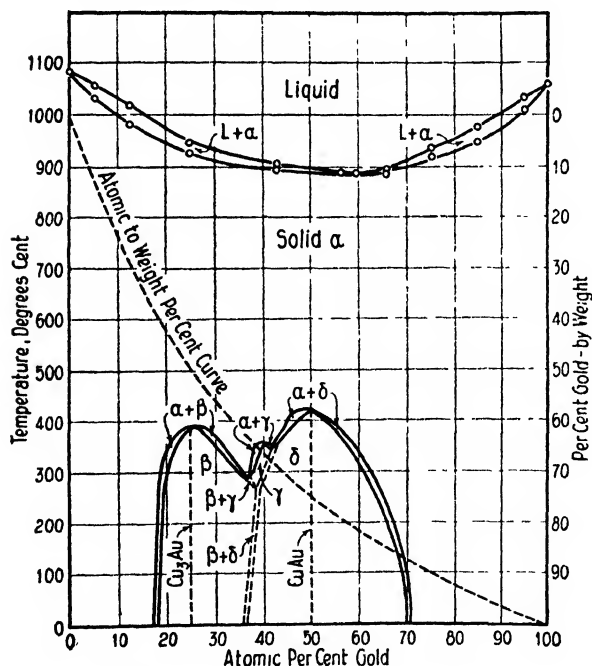


Fig. 1—Gold-Copper Constitution Diagram.

represented a continuous series of solid solutions with a minimum in the solidification interval at 40.5 atomic per cent of copper.

Kurnakow¹ and some of his associates had, in connection with their early investigations, noted that some of their specimens in the region of equal atomic per cent concentration showed unusual hardness values. Kurnakow, Zemczuzny, and Zasedatelev² reinvestigated the system and published their results in 1916. On

Matthiessen¹ seems to have been one of the first to investigate this system. His work related to the microstructure and electrical conductivity of wire drawn from cast alloys and was published in 1861. Alloys in this system were also studied by Roberts-Austen and Osmond² in 1896, by Heycock and Neville³ in 1897, and by Roberts-Austen and Rose⁴ in 1901. These investigators concluded that gold and copper form a continuous series of solid solutions. The freezing point curves were studied by Heycock and Neville³ and by Roberts-Austen and Rose.⁴

In 1907 Kurnakow and Zemczuzny² published the results of their careful determinations of the liquidus and solidus lines of these alloys and concluded that they represented

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checking the liquidus and solidus lines the values were found to agree with their previously published data. These values are shown in Fig. 1.* They found, however, differences in the hardness, electrical conductivity, and other properties of the quenched and slowly cooled alloys.

As a result of an extensive series of experiments, they concluded that the system in the stable form at ordinary temperatures has two intermetallic compounds, Cu_3Au and CuAu . These compounds were found to form on slow cooling or on reheating the quenched alloys. Their work outlined the region of stability of each of these compounds and showed a good correlation between such physical properties as hardness, electrical resistance, thermal conductivity, and the proposed constitution diagram. Their hardness curves of the quenched and slowly cooled alloys are shown in Fig. 2 along with their electrical resistance curve for the quenched alloys. These investigators determined the temperature of the formation of the compounds by means of cooling curves, and later investigations have shown that there is a hysteresis effect in the formation of these compounds. Therefore, the regions outlining the existence of the compounds shown in Fig. 1 are taken from the more recent investigation by Haughton and Payne,¹⁰ which, although based on electrical conductivity measurements in which the transformations were studied both on heating and cooling, are thought to represent more nearly the equilibrium conditions.

Portevin and Durand¹¹ had started an investigation of this system at the beginning of the war, but the work was interrupted, and before it could be renewed the researches by the Russian investigators⁹ had been published. Portevin and Durand, however, pointed out that gold alloys containing 20-30% of copper by weight were often brittle and could not be cold worked, but after quenching from a temperature above which these compounds formed, the alloys could be cold worked satisfactorily.

The gold-copper system has been studied extensively in connection with various theories concerning the ability of noble metal atoms to protect baser metal atoms from corrosion. Tammann¹² referred to these alloys in his work as early as 1918.

In connection with Tammann's study^{12, 13, 14} on corrosion, he concluded that 2/8 molecular gold concentration was the minimum which prevents solution of the

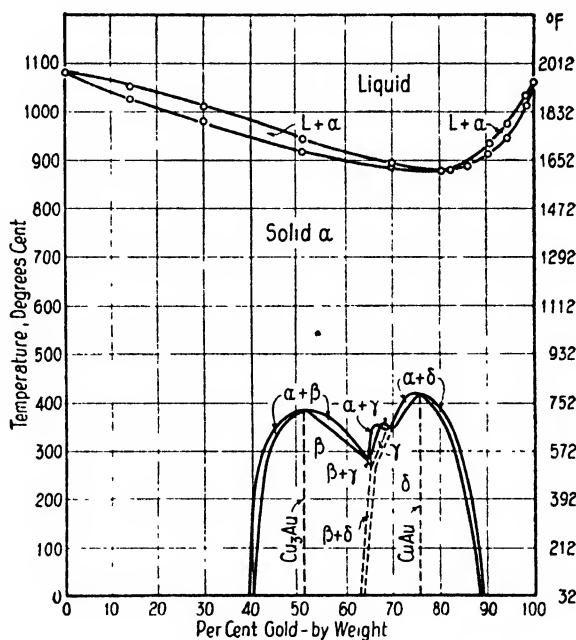


Fig. 1-A—Gold-Copper Constitution Diagram with concentration in weight per cent.

*For convenience in showing the intermetallic compounds in gold-copper alloys the concentrations in Figs. 1 and 2 are plotted in atomic per cent; however, in order to make the correlation between these diagrams and the more usual methods of showing concentrations, Fig. 1-A has been included, in which the concentrations are given in weight per cent.

copper ions. With strongly oxidizing agents he found that $4/8$ molecular gold concentration was necessary to prevent corrosion. Tammann's work was all based on the assumption of regular atom distribution of the gold and copper atoms in the face-centered cubic lattice.

A more recent investigation by LeBlanc, Richter, and Schiebold¹⁸ does not confirm the application of Tammann's theory to the gold-copper alloys. They found little difference in the corrosion resistance of tempered and untempered alloys. No sharp resistance limits were found in the alloys of different atomic concentrations.

On the other hand, Graf's work^{16, 17} on single crystals tended to support Tammann's theory, except when the corrosion was at increased temperatures, which might cause atom migration. X-ray examination of some of Graf's corroded specimens showed the gold lattice only, and some of them showed "superstructures."

Bain^{19, 20} discussed the gold-copper system in connection with his papers on "The Nature of Solid Solutions", "Cored Crystals and Metallic Compounds", and "Crystal Structure of Solid Solutions".

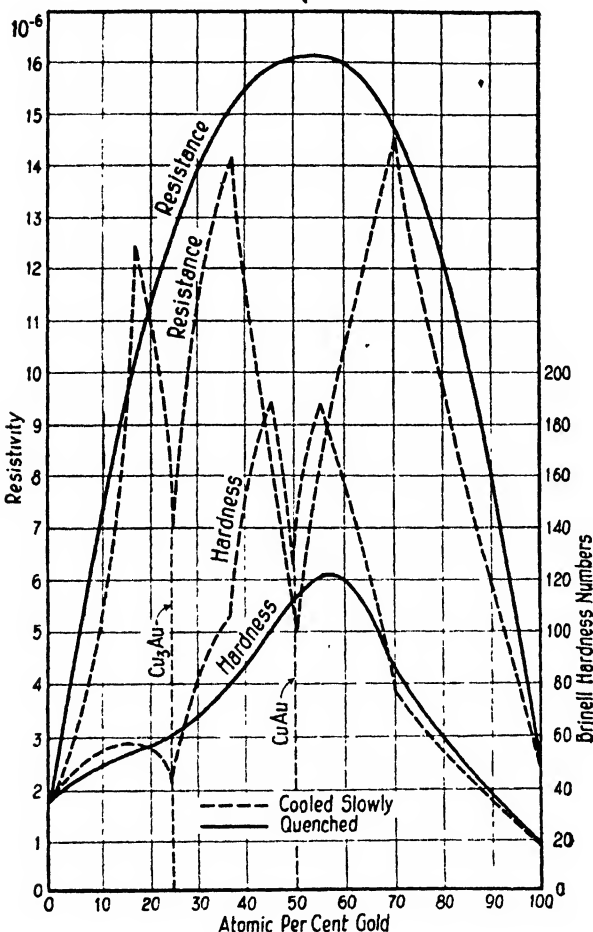


Fig. 2—Hardness and electrical resistance of slowly-cooled and quenched gold-copper alloys.

From the results of X-ray analysis he observed that the unit parameter of the alloys was generally lower than the straight line relation between the unit parameters of gold and copper when the concentration is plotted by atomic per cent. He studied the alloys containing 25 atomic per cent of gold and suggested that the gold atoms in the slowly cooled alloy occupy half of the positions in alternate 111 planes, which he referred to as "planes of greatest symmetry".²⁰ He observed that the concentration of the gold atoms in certain planes should give some special lines corresponding to a "superstructure" composed of gold atoms in the lattice. In some of his alloys he noted faint lines, which he attributed to such a "superstructure".

Smith²¹ studied the unit parameters of a series of alloys annealed 2 hr. at 600°C. and then quenched, and found that the values were all above the straight line connecting the values for the pure metals. He was unable to prepare either of the compounds in the pure form, but observed in the slowly cooled alloys of equal atomic concentration, lines which fitted the tetragonal lattice with a c/a ratio of 0.86.

The extent of the beta field in Fig. 1 was placed at 22.5-35 atomic per cent of gold by Kurnakow, Zemczuzny, and Zasedatelev.⁹ More recent investigations by Kurna-

kow and Ageew²² placed these limits as 22-40 atomic per cent of gold. The recent investigations by Haughton and Payne¹⁰ fixed the limits of field as 17.5-36.5 atomic per cent of gold, as they are shown in Fig. 1. Kurnakow, Zemczuzny, and Zasedatelev⁹ originally established the field of existence of the delta-phase (CuAu) as 42-65 atomic per cent of gold. Kurnakow and Ageew²² placed the range at 42-70 atomic per cent of gold, while Haughton and Payne¹⁰ have placed this limit at 36.5-71 atomic per cent of gold, as shown in Fig. 1. The gamma region, which might represent Cu₃Au, was noted by Haughton and Payne¹⁰, but the character of this possible phase has not been determined.

Kurnakow, Zemczuzny, and Zasedatelev⁹ placed the maximum temperature for the formation of Cu₃Au at about 371°C. and that for CuAu at about 367°C. Borelius and his associates²³ found the $\alpha \rightleftharpoons \beta$ transformation in the 25 atomic per cent gold alloy at 382°C. on cooling and 390°C. on heating. They observed the $\alpha \rightleftharpoons \delta$ transformation, the 50 atomic per cent gold alloy, at 400°C. on cooling and at 430°C. on heating. The temperatures of these transformations, as determined by Haughton and Payne,¹⁰ are those shown in Fig. 1. These values are admittedly tentative. They estimated that the Cu₃Au transformation was

probably accurate to $\pm 3^\circ\text{C}$. Owing to the hysteresis noted in the CuAu transformation, it was considered that the values obtained on heating were more reliable and the curves were drawn accordingly, but the equilibrium temperature was considered less accurate than in the case of the Cu₃Au transformation.

With further regard to the crystal structure, there is rather general agreement that the beta-phase (CuAu) has the face-centered cubic arrangement. Some investigators have failed to show this transformation and have questioned the existence of this phase, but the more detailed investigations seem to establish its existence without question. The rate of transformation is, however, slower than in the case of the transformation from the alpha to the delta phase.

Johansson and Linde^{24, 25} have suggested that the arrangement of the atoms in Cu₃Au is face-centered cubic with the gold atoms at the corners of the cube and the copper atoms at the center of the faces. The space lattice of copper, which is face-centered cubic with a unit parameter or cube edge of 3.61 Angstrom units, is shown in Fig. 3-A, while the lattice for Cu₃Au is shown in Fig. 3-B. The lattice remains face-centered cubic, but the gold atoms of larger diameter have expanded the unit parameter to 3.75 Angstrom units. This arrangement satisfies the requirements with reference to the atomic concentration and results in a "superstructure" with concentration of the gold atoms in the 001 and 110 planes, as can be seen in Fig. 3-B. A similar atomic arrangement has been proposed by Seemann and Vogt,²⁶ who noted in certain cases superimposed structural lines.

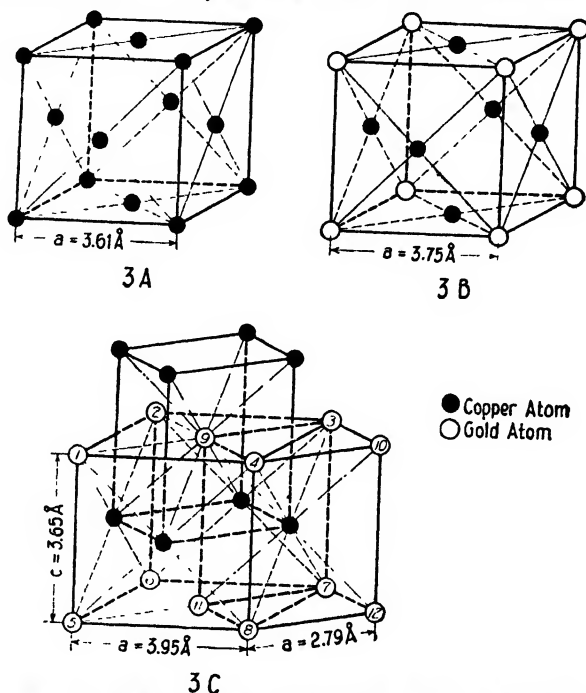


Fig. 3—Crystal lattices of gold-copper alloys. A. Copper 100%. Face-centered cubic lattice. B. Copper 75 and gold 25 atomic per cent (Cu₃Au). Face-centered cubic lattice. C. Copper 50 and gold 50 atomic per cent (CuAu). Face-centered tetragonal or body-centered tetragonal lattice.

With reference to the crystal structure of the delta-phase (CuAu) there is a lack of complete agreement. Preston's work²⁷ on an alloy containing 51.2 atomic per cent of gold showed that an alloy thoroughly annealed at 400°C. and quenched gave the face-centered cubic lattice with a unit parameter of 3.94 Angstrom units. On specimens cooled slowly from 700°C. he observed the body-centered tetragonal lattice with "a" equal to 2.79 Angstrom units, and the axial ratio $c/a = 1.31$. This would seem to be in agreement with Masing's findings,²⁸ in which he suggests that the tetragonal lattice is formed by compressing the tetragonal group, which is present in the face-centered cubic lattice, in the direction of the "c" axis, and filling half of the planes perpendicular to the "c" axis with gold atoms. This arrangement results in a concentration of the gold atoms in the 110 and 001 planes and should result in a "superstructure".

On the other hand, Johansson and Linde^{24, 25} reported a tetragonal face-centered arrangement of the atoms in the delta-phase (CuAu) with an axial ratio of 0.926. Likewise, Gorski²⁶ found a tetragonal lattice, but without systematic distribution of the copper and gold atoms, to be the stable form below 385°C. He noted that the c/a ratio changed from 0.935 at 380°C. to 0.926 at 300°C. Dehlinger and Graf,³⁰ using electrical conductivity methods, noted the transformation in the 50 atomic per cent alloy, which they considered must be due to valence electrons.

Ohshima and Sachs³¹ studied the structure of alloys containing 49.3 atomic per cent of gold, which were quenched from 350-300°C. They noted a tetragonal lattice $a = 3.95$ Angstrom units, $c = 3.68$ Angstrom units and $c/a = 0.932$. They also noted that the axial ratio varied with the temperature. They found a similar value when single crystals were examined.

Eisenhut and Kaupp³² have studied these alloys using electron emissions from a hot cathode, and observed that the copper-gold alloys of 1:1 atomic ratio, deposited on mica from the vapor phase, developed a tetragonal structure with superstructure lines after annealing 1 min. at 225-400°C. They reported that when this alloy was heated to 450-500°C. the tetragonal structure is converted into a structure of the zinc blend or diamond type with a unit parameter of 5.40 Angstrom units.

Thus, there seems to be rather general agreement with reference to the structure of the beta-phase (CuAu), but some disagreement as to the structure of the delta-phase (CuAu). Some investigators contend that the arrangement is body-centered tetragonal with an axial ratio of about 1.31, and others that it is a face-centered tetragonal arrangement with an axial ratio of $c/a = 0.926-0.932$; these crystal units, however, are essentially equivalent. Both of these groupings can be noted in models, as was pointed out by Preston.²⁷

In both cases it is necessary to compress the original face-centered cubic lattice in the direction corresponding to the "c" axis of the tetragonal lattice. This condition is satisfactorily provided for by placing the gold atoms in alternate planes perpendicular to the "c" axis, as is shown in Fig. 3-C. In this case the resulting tetragonal unit cell contains gold atoms at the corners (gold atoms 1-8, Fig. 3-C) and at the centers of the two faces which have not been compressed, while the four faces which have been compressed will contain copper atoms. This arrangement gives a cell comprising four atoms, two of which are gold, and the remaining two are copper. The tetragonal body-centered grouping is also present in the model in which the unit cell contains a gold atom in the center and copper atoms at the corners, or vice versa. This arrangement is shown in Fig. 3-C with the gold atoms (9-3-10-4-11-9-12-8) at the corners and a copper atom in the center. Another tetragonal body-centered group is also shown with a gold atom (9) at the center and copper atoms at the corners.

It is, therefore, evident that there is no essential difference in the atomic arrangement, depending upon the system being face-centered tetragonal with a c/a ratio of about 0.93 or a body-centered tetragonal with a c/a ratio of about 1.3; perhaps the former is somewhat easier to visualize. Either arrangement will give the same symmetry and the same possible "superstructure".

The possibility of heat treating gold-copper alloys to produce certain desired physical properties was indicated by the researches of Kurnakow, Zemczuzny, and Zasedatelev⁹ in 1916, and the application of this method for controlling the properties of dental golds containing considerable amounts of copper was pointed out by the present author²³ in 1923.

It is now known that the hardening of alloys by atomic rearrangement is not unique in the gold-copper system, but that other systems, for example copper-platinum and copper-palladium, show a similar phenomenon.

Recent Progress—Since the above manuscript was prepared in 1932 there has been considerable research on metal structures and superlattices have received much attention. There does not seem to be justification for changing the material originally presented but some slight additions may be made.

Superlattices have been reviewed by Nix and Shockley and by Barrett²⁴ and these reviews supply adequate references to the literature on the subject.

The more recent researches have not materially changed the information regarding the beta phase (Cu₃Au) as represented in Fig. 1. However, the change from the random arrangement of alpha appears to be simply to an ordered arrangement. Experimental data indicate that the face-centered cubic cell has copper atoms in the faces and gold atoms at the corners. While, as mentioned above, there does not now appear to be any change in the type of lattice in the alloys corresponding to approximately the Cu₃Au composition, certain discontinuities in properties such as specific heat and electrical conductivity have been observed in the temperature range of about 250-390°C. by Sykes and Jones²⁵ and by Sykes and Evans²⁶ which are not entirely consistent with the usual theories for a simple change from random to ordered atomic arrangement.

In the case of the delta phase (Cu-Au) in Fig. 1, some new information has been obtained. Johansson and Linde²⁷ have reported not only the tetragonal lattice previously reported but have also reported on orthorhombic structure in the 53 atomic per cent gold alloy in the range of about 420-380°C. which slowly changes into the tetragonal lattice in the range of 200-380°C. These authors have also reported the orthorhombic structures in alloys containing 47-53 atomic per cent of gold rapidly cooled after annealing at 410-420°C. and in alloys containing between 36 and 47 or between 53 and 65 atomic per cent gold annealed in the temperature range of 400-200°C.

Unpublished researches by Hultgren and Tarnopol show the ordered orthorhombic lattice in the Cu-Au alloy at 400 and 390°C., the tetragonal lattice in the range of 350-300°C., and the presence of both lattices at 375°C. Hultgren and Tarnopol have obtained the orthorhombic and the duplex lattices by both heating and cooling into the selected temperatures so that their evidence seems quite convincing. Long annealing times were required to establish equilibrium conditions so that good X-ray lines were obtained. The following data from Hultgren and Tarnopol show some of their results for the 50 atomic per cent alloy:

Annealed, °C	Days Annealed	b/a ratio	b/a after 6 Months at Room Temperature
400	13	1.018	1.031
390	24	1.017	1.026
375	37	1.025	1.027

From the above data, it appears that the orthorhombic structure can be preserved at room temperature but that it undergoes a slight change in axial ratios.

This new information indicates that the region in Fig. 1 designated as delta will have to be modified to show the region of the orthorhombic lattice but the data are as yet hardly adequate for location of the areas.

If a phase change is based upon a change in lattice as the criterion, then there are phaseal modifications of the Cu-Au alloy and also for alloys ranging from about 36 to 65 atomic per cent gold. There is some indication that careful microscopic work may support the X-ray studies which have been made on the Cu-Au alloys of about equal atomic concentrations.

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Constitution of Gold-Silver Alloys

By Robert H. Leach*

Native alloys of gold and silver occur in many different parts of the world and consequently were among the first metals worked by prehistoric races. The alloys are malleable and ductile. The yellow color changes to a series of light green shades as the percentage of silver is increased and at 50% silver by weight, the color is nearly white.

Gold and silver can be alloyed in all proportions to form a continuous series of solid solutions.

The early investigators of this system, W. C. Roberts-Austin and T. K. Rose,¹ C. T. Heycock and F. H. Neville,² and others determined the freezing points of different compositions and their diagrams showed a single continuous curve between the melting points of gold and silver. More recently, Raydt,³ V. Fischer,⁴ L. Sterner-Rainer,⁵ W. Broniewski and K. Wesolowski⁶ have determined the solidus and liquidus points. The constitution diagram selected is based upon the work of Broniewski and Wesolowski, and is in close agreement with that of Sterner-Rainer. Although these investigators report small differences, they are in general agreement that the solidus and liquidus curves are parallel a few degrees apart and converge near the extremities of the diagram.

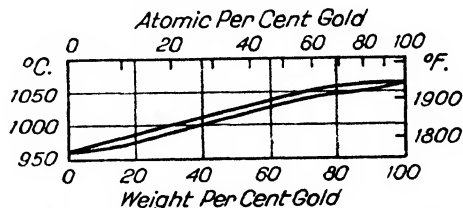


Fig. 1—Constitution Diagram for Gold-Silver Alloys.

X-ray examinations show that all of the gold-silver alloys have a face-centered cubic lattice. H. Weiss⁷ made an X-ray study of the system by the powder method and found a continuous variation in lattice dimensions from pure gold to pure silver. S. Holgersson⁸ found that the variation in lattice dimensions corresponds closely to a linear function of the atomic composition. He reported 4.080 Å as the lattice constant for pure gold and 4.076 Å for silver. G. Sachs and J. Weerts⁹ determined the lattice constants over the entire range of composition. They found the value for pure gold to be 4.0700 Å, and silver 4.0776 Å, and a minimum of 4.0672 Å at 19.9 weight per cent silver. M. LeBlanc and W. Erler¹⁰ confirmed the results obtained by Sachs and Weerts; finding a parabolic variation of the lattice parameter with the composition. Their determinations, however, show the minimum at approximately 35.5 weight per cent silver instead of 19.9.

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Gold Alloys

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Pure gold when annealed has a tensile strength of only 16,000-17,000 psi., a Brinell hardness of about 30, and a density of 19.3. For most industrial purposes gold is alloyed with other metals to produce a harder material of lower density and lower cost. Where silver or base metals are employed for alloying, a reduction in nobility and tarnish resistance results. Where high resistance to corrosion or a high melting point is required or other special requirements are to be met, platinum or palladium are employed as alloying elements rather than silver or base metals.

Alloys of 14 carat or above are quite resistant to nitric acid while 12 carat jewelry alloys are marginal and their behavior depends upon the major alloying elements. Ten carat alloys may be considerably attacked. This behavior of gold alloys, and analogous tests using a mixture of nitric and hydrochloric acids (aqua regia) to attack the more resistant alloys are employed for quickly judging the quality of gold articles. Comparisons are made of the behavior of a streak made by rubbing the unknown gold alloy on a corrosion resistant stone and comparing its behavior in contact with acid with that of similar streaks made with a series of alloys of known composition. Many small lots of used gold articles change hands on the basis of this test which is described in detail in the book, "Testing Precious Metals."⁴

By proper selection of the alloying elements, gold alloys of considerable range in color can be had, from the yellow of pure gold to fair reds, greens, and good whites. These colored golds are important in jewelry.

The quality of gold alloys is commonly expressed in terms of carat or fineness. The carat is the proportion of gold expressed in twenty-fourths while the fineness is the proportion of gold expressed in thousandths. Pure gold is 24 carat or 1000 fine or 100% gold, while 12 carat gold is 500 fine and contains 50% gold.

Gold is frequently employed in clad form, welded or soldered to a base metal and is then called "gold filled" or "rolled gold plate." The quality or the ratio of the weight of the gold alloy coating to the total is expressed as a fraction. For example, $\frac{1}{10}$ 12 carat "gold filled" is surfaced with a layer or layers of 12 carat (50.0% gold) gold alloy weighing 10% of the weight of the composite article, which if assayed in toto would contain 5% gold. The designation "gold filled" is limited by stamping regulations to articles in which the weight of the coating is at least $\frac{1}{20}$ of the total, while lower ratios may be stamped "rolled gold plate." In any event, a quality mark cannot be applied to articles surfaced with a gold alloy under 10 carat. For further details regarding the stamping of clad articles, reference 15 should be consulted.

Watch cases require rather substantial cladding to resist wear and the present basis for classifying such stock is to designate products surfaced with at least 0.003 in. on the outside and 0.001 in. on the inside of 10 or higher carat gold alloy as "gold filled" and to designate cases surfaced with half this thickness on the outside and none inside as "rolled gold plate."

Base metals electroplated with a gold alloy usually have a far thinner coating than provided in rolled gold plate, but methods are available for producing electroplates of the same thickness as those typical of "gold filled" stock and some use is made of this method.

Melting, Casting, and Rolling⁵.—For industrial purposes gold alloys are usually melted in clay graphite crucibles heated in a gas fired furnace although some types of electric furnaces are also employed and recently renewed interest in high frequency melting has become apparent. With gold-silver-copper alloys, charcoal is at times used as a cover to avoid oxidation although a reducing flame plus a protective cover of boric acid is generally preferable. The small amount of zinc usually present in the alloy functions as a deoxidizer but where it is inadequate about 0.05% of calcium boride may be added just before pouring. Many of the dental alloys are damaged by the trace of silicon which may be reduced from the crucible and therefore must be melted in lined crucibles. Lead, sulphur, and other impurities are very damaging to gold alloys and must be excluded by the use of very pure alloying metals and precautions in handling scrap.

The alloys to be rolled are cast by slowly pouring the metal into warmed cast iron molds lightly greased with castor oil and the ingots are pickled prior to cold

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rolling. The casting of thin and wide ingots is frequently attempted but usually leads to the production of material containing shrinks which show up later. Ingots about $\frac{1}{2}$ in. thick and up to 2 in. wide are more appropriate than thin, wide ingots.

Cold rolling presents no special problems except that adequate reductions between anneals, preferably at least 50%, must be employed with white gold to avoid fire cracking. Annealing may be carried out in a nonoxidizing atmosphere or if not, the surface may be protected with a layer of ochre and boric acid which is pickled off after annealing. Some alloys, particularly those high in copper, require rapid cooling to yield maximum ductility and are quenched in hot water after annealing. Quenching is apt to crack white golds and some other compositions are also tender.

Certain types of rings, particularly men's signets or others produced in limited quantities, are made by casting gold into molds made of very fine sand while dental castings are produced in molds made of silica bonded with plaster of Paris. The latter castings are made by the so-called "lost wax process" in which a wax model is invested in a plastic mass of plaster and silica which is permitted to harden. The mold is then heated to drive out the wax and the gold alloy is melted with a gas-air torch and forced into the preheated mold by air pressure or centrifugal force. The amount and type of silica and the preheating temperature are adjusted to provide sufficient expansion to compensate for the shrinkage of the gold to yield a casting of the same size as the original wax model.

Principal Useful Gold Alloy Systems

Gold-Silver^{1, 2}—Gold and silver form a continuous series of soft, solid solutions. The maximum strength of the annealed alloys is but 30,000 psi. The liquidus and solidus are close together and rise slowly from 960°C. at the silver end to 1063°C. at the gold end. This system is discussed in detail on page 1503. The 18 carat (75% gold) alloy has an attractive green color and is sometimes used for jewelry decoration. Further increase in silver content yields paler alloys. The 12 carat (50% gold) alloy is an unattractive greenish white which tarnishes readily. Some use has been made of the 20 and 30% gold-silver alloys for electrical contacts but their resistance to tarnish is poor. The 70% gold-6% platinum-24% silver alloy has been widely used for electrical contacts in telephone equipment and is excellent, but has been replaced by pure palladium which can be used at higher currents and is less costly.

Gold-Copper^{1, 3}—A continuous series of solid solutions is formed at high temperatures but transformations occur at low temperatures yielding ordered phases based on AuCu and AuCu₃. Copper rapidly hardens gold. The maximum strength in the annealed state is about 75,000 psi. and is found at 18 carat (75% gold). Slow cooling or aging at about 300°C. causes alloys in this vicinity to harden and become rather brittle so that it is necessary to quench or rapidly cool such alloys prior to cold working. The liquidus and solidus lie close together and pass through a minimum of 880°C. at 80% Au. Further data on the equilibrium are to be found on page 1496.

The addition of copper to gold yields alloys with a red cast and the 18 carat (75% gold) and lower carat alloys find some decorative application as red golds. The 90% gold-10% copper alloy was formerly used for coinage in a number of countries. The 12 and 14 carat gold-copper alloys containing about 6% nickel possess an attractive pink color and have been quite popular for spectacle frames.

The tarnish resistance of the gold-copper alloys is of the same order as that of the gold-silver alloys.

Gold-Nickel^{3, 4, 5, 6}—A continuous series of solid solutions is formed at high temperatures but this decomposes into gold-rich and nickel-rich solid solutions of variable composition at low temperature with consequent changes in corrosion resistance, color and hardness. The quenched solid solution alloys are quite hard. A maximum hardness of about 350 Brinell hardness is observed in the middle of the series. The liquidus and solidus pass through a minimum of 950°C. at 82.5% gold.

The addition of nickel to gold rapidly effaces the yellow color and the 75% gold-25% nickel has a pleasing white color when quenched. The color deteriorates with a further increase in nickel content. The simple binary gold-nickel alloys are not useful but derived alloys containing copper and zinc yield the white golds of commerce which had a great vogue in jewelry as platinum substitutes. The high hardness of white golds of good color and their propensity to fire crack make them difficult to work. Currently, these alloys have lost popularity to the yellow golds and to platinum and palladium for white jewelry.

Gold-Palladium¹—A continuous series of solid solutions is formed which is stable at all temperatures. All of the alloys are very ductile and the maximum strength of 50,000 psi. in the annealed state is observed in the middle of the series. The liquidus and solidus rise rapidly upon the addition of palladium to gold. This is one of the reasons for the frequent addition of palladium to complex gold alloys as most of the other alloying additions tend to depress the melting range to an undesirable extent. Palladium also markedly improves the tarnish resistance of silver and base metal content dental and jewelry alloys.

Palladium lightens the color of gold and yields a number of white alloys which are, however, less brilliant than the nickel content white golds. The corrosion resistance of the palladium golds is excellent and some use has been made of the 70-80% gold binary alloys and particularly ternary alloys containing platinum for crucibles and chemical equipment including rayon spinnerets. The 80-85% gold-palladium alloy has mechanical properties similar to those of 22 carat gold and finds use in dentistry where a white, easily worked sheet material is required.

Gold-Platinum^{2, 3}—While a continuous series of solid solutions is formed at high temperature, complicated changes occur at lower temperature which cause considerable hardening and working difficulties in alloys containing less than 70% gold unless palladium, which extends the range of useful alloys, be present. Small amounts of platinum added to gold cause little increase in hardness but amounts above 30% cause a rapid rise in hardness to above 300 Brinell hardness at 70% platinum. The liquidus and solidus rise upon the addition of platinum but do not lie close together so that marked coring, difficult to eliminate, develops on casting.

The 70% gold-30% platinum alloy has been most useful and is widely used for rayon spinnerets although the relative prices of gold and platinum are currently such as to render the use of platinum rich alloys more economical and they are being introduced.

Gold-Zinc⁴—These elements form a system somewhat analogous to that formed by copper and zinc but complicated by the formation of several ordered phases at low temperature. The simple binary alloys find no commercial use but considerable percentages of zinc are frequently present in white and low carat green golds to aid in developing the desired color and in solders where it functions to lower the melting point. About 1% zinc is present in many dental golds where it aids in deoxidation and improves the mechanical properties and aging response of certain analyses.

Gold-Silver-Copper—See also references 1, 3, 5, 7, 9, and 10. This ternary system comprises a solid solution region extending along the gold-silver and gold-copper sides plus a duplex area extending out from the eutectic on the silver-copper side. The high carat alloys are solid solutions at high temperature, but may contain an ordered phase derived from AuCu at low temperatures. The low carat alloys may contain some eutectic. The melting temperature is generally rather low while the tarnish resistance depends principally upon the gold content. At 14 carat (58.3% gold) the maximum strength (in annealed material) of 78,000 psi. is secured when equal quantities of silver and copper are present.

The dental industry has used large quantities of 22 carat (91.6% gold) plate for crowns and similar restorations while alloys containing 70-90% gold with silver and copper the principal alloying elements form the basis of cast inlay golds. Strong yellow denture golds contain 80-70% gold, together with 2-12% of platinum or palladium to improve their properties. White alloys containing substantial quantities of palladium replacing corresponding amounts of gold are now in general use. These alloys contain from 15% gold with 25% palladium to 30% gold with 15% palladium, together with small amounts of platinum, 1% zinc and silver and copper the remainder.

In the jewelry trade, 18 carat alloys will range from the hard red golds containing copper as the principal alloying element, through the yellows with roughly equal quantities of silver and copper to the greens containing silver as the principal alloying element. The strength and hardness fall steadily with an increase in silver content. At 14 carat the red golds will contain copper as the principal alloying element. As the silver content is increased and copper decreased, a series of yellow golds of various shades is produced; those containing approximately equal quantities of silver and copper possess a greenish yellow color which has become popular in recent years. Further increase in the content of silver to 30-35% with copper the remainder yields greenish alloys. The green color produced in such alloys is far less attractive than that of the 18 carat gold-silver alloy. Small

Tensile Properties of Selected Gold Alloys

Type	Composition, Weight per cent				State	Yield Point, Psi.	Tensile, Psi.	Elongation, %	Brinell Hardness, No.	Reference
	Au	Ag	Cu	Ni	Zn	Pd	Pt			
24 carat	100	.....	.....	.....	.....	.....	.....	Nil	16,900	45.0
18 carat, green.....	75.0	25.0	.....	.....	.....	.....	.....	30,000	31,400	4.2
18 carat, yellow.....	75.0	12.5	12.5	.....	.....	.....	.....	Very low	27,000	36.1
18 carat, red	75.0	.....	25.0	.....	.....	.....	.....	41,000	49,000	2.6
18 carat, white.....	75.0	.....	3.5	16.5	5.0	.....	.....	39,500	73,000	4.6
14 carat, green.....	58.3	35.7	5.8	.....	.....	.....	.....	35,500	73,000	4.6
14 carat, green ^a	58.3	30.0	6.0	1.5	4.2	Mn 0.1	.....	115,000	121,000	3.2
14 carat, greenish yellow ..	58.3	20.7	20.7	.....	.....	.....	.....	76,500	121,000	3.2
14 carat, light yellow.....	58.3	11.0	26.4	2.0	2.3	.....	.....	31,000	96,000	41.5
14 carat, white.....	58.3	.....	17.0	17.6	7.0	Mn 0.15	.....	124,000	127,000	1.4
22 carat, yellow dental plate	91.7	5.3	3.0	.....	.....	.....	.....	82,000	101,000	1.4
Soft white dental plate.....	85.0	.....	.....	.....	.....	.....	.....	104,000	109,000	2.0
Yellow wrought dental wire ..	70.8	15.5	13.2	.....	0.5	.....	.....	39,000	64,000	34.9
Yellow wrought dental wire ..	63.8	15.5	13.2	.....	0.5	.....	7.0	110,000	113,000	2.4
White wrought dental wire ^b ..	49.0	17.8	15.5	.....	0.5	17.6	.....	52,500	80,000	32.0
White wrought dental wire ..	60.0	9.0	12.0	.....	2.0	12.0	5.0	91,500	104,000	10.5
White wrought dental wire ..	55.0	8.0	12.5	.....	1.0	7.5	17.0	45,500	78,000	34.3
Initial casting gold.....	90.0	1.5	7.0	.....	0.5	.....	1.0	116,000	121,000	3.1
Denture casting alloy	70.0	11.0	11.0	.....	1.0	3.0	4.0	185,000	190,000	50.0
Lenture casting alloy.....	15.0	45.0	15.0	.....	1.0	24.0	.....	105,000	105,000	2.5
Spunnet alloy.....	66.7	.....	.....	.....	.....	.....	33.3	50,000	81,000	5.0
^a Aged at 325°C. for 30 minutes. ^b Aged at 400°C. for 15 minutes.										

quenched from 450-250°C. in 30 minutes.

amounts of zinc added to the above tend to lighten the colors but this is generally not desired.

The introduction of a substantial percentage of zinc (from 3-15%) is useful in developing green and yellow alloys of lower carat and yields materials which are age hardenable.

The strength of the annealed 14 carat gold-silver-copper alloys reaches a maximum at about 20% copper but the melting temperature (solidus) is only about 830°C. at this point and drops slightly lower at 15% copper. For this reason the use of alloys of this type requires care to avoid damage in soldering and necessitates the use of low melting solders which may be rather easily tarnished. The introduction of small percentages of palladium raises the melting point and it has been added to 12 and 14 carat alloys for this reason and also to increase resistance to tarnish.

Dental alloys containing copper and the platinum metals as well as many of the colored jewelry golds are age hardenable. They can be softened by annealing at about 700-750°C. and quenching and hardened either by slow cooling or better by reheating for 15-30 minutes at 300-450°C. This treatment is particularly effective in increasing the elastic limit and yield point which in appropriate alloys can be raised to values in excess of 100,000 psi. Age hardening is widely employed in dentistry and is essential to develop the strength required, but although it was first applied fifteen years ago, it has not been used in jewelry manufacture as widely as it should be.

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Properties of Gold-Copper-Nickel-Zinc Alloys

(White Gold)

By A. W. Peterson†

The white gold alloys may be broadly divided into two types according to use; namely, the dental golds and the jewelry alloys. The former contain a relatively large amount of the platinum group metals to develop strength, ductility and corrosion resistance, while the latter today contain practically no metals of this group.

Origin—The white gold alloys in substantially the form used today in the manufacture of jewelry originated as a measure of economic necessity near the close of the World War. White alloys had been in use for jewelry for some years in Europe, but these goods were of the platinum and palladium type. Also gold alloys using nickel and cobalt as decolorizers were slightly known in Germany in 1912.¹ But the great demand for platinum, heretofore the popular white jewelry metal, for war purposes had made the metal scarce and the price prohibitive; more than ever a substitute was desirable. After many experimental failures and successes, the production of gold alloys using nickel as a decolorizer was achieved on a commercial scale, as shown by the United States, Canadian, and British patents. These alloys became popular and have retained much of their popularity to the present day.

These alloys were first used in rings, which are cast, but today most of the white gold alloys are used in the wrought condition, and the greater portion of such material is employed in the duplex metals, such as "gold filled" and "rolled gold" plate. The principal products are watchcases, bracelets, cigarette cases, pens and pencils, and optical goods. At present the greatest demand is for optical frames, in which the colors range from an inconspicuous pink to a bluish white.

Most of the white gold alloys produced are 10, 12, and 14 karat gold, and some 18 karat. This corresponds to 10, 12, 14, and 18 parts of fine gold for every 24 parts of total alloy. The base metals used are copper, nickel, and zinc.

Constitution—The constitution of the white gold alloys of the Au-Cu-Ni-Zn class is difficult to analyze exactly due to the number of combinations of the component elements that are possible. At higher temperatures (above 700°C.) these alloys are homogeneous solid solutions, but upon slow cooling to room temperature, or by low temperature (350-400°C.) aging, complex structures are formed.^{2,3} These alterations in structure are accompanied by changes in hardness and electrical resistivity. It has been shown that these alloys respond to the usual treatments that cause precipitation hardening.² This hardening is probably a combined effect of the formation and subsequent precipitation of compounds of AuCu and AuZn, or more complex compounds, as well as the separation of solid solutions from the complex matrix.^{3,4}

Physical and Mechanical Properties—The physical and mechanical properties of the white gold alloys vary according to the karat and the changes in base metal proportions. This fact is illustrated by Table I showing the density and mechanical properties of several alloys. These alloys have been annealed for one-half hour at 705°C. and air cooled except as noted.

Table I
Properties of White Gold Alloy

Composition, %					Brinell Hardness No.	Y.P. psi.	T.S. psi.	Elong in 2 in., %	Refer- ence
Au	Ni	Cu	Zn	Sp.Gr.					
75.00	13.5	8.50	3.0	14.9	178	80,800	115,400	34	(5)
75.00	18.0	4.00	5.0	14.8	182	86,000	102,000	35	**
58.33	18.0	25.67	1.0	13.0	177	73,000	101,000	30	**
58.50	15.3	25.80	0.4	13.02	177	72,960	101,250	29	(5)
58.33	17.0	15.67	9.0	12.5	171	65,000	109,000	38	**
58.35	17.0	16.00	8.65	....	...	64,500*	105,000	43	(3)
58.33	12.5	24.17	5.00	12.8	145	59,000	103,000	46	**
58.50	14.5	20.0	7.00	12.8	152	60,900	105,300	41	(5)
50.00	18.0	22.0	10.00	11.9	149	61,000	103,500	43	(5)
50.00	18.0	29.0	6.00	11.8	145	60,000	102,000	43	**
50.00	10.25	34.0	5.75	11.9	130	55,000	93,000	46	**
41.67	17.50	33.83	7.00	11.2	120	55,000	95,000	37	**

*Annealed at 750°C.

**From General Plate Co.

†Metallurgist, General Plate Co., Attleboro, Mass.

Technology—The white gold alloys require extreme care in the choice of raw materials and processing technique. Only pure electrolytic copper and nickel free from sulphur and carbon, and highly refined zinc, should be used in the manufacture of the base metal alloy noted below. The gold used must be of mint fineness.

Best results in melting are obtained by alloying the fine gold with a previously manufactured base metal alloy of the correct composition. The actual fusion is conducted under a heavy flux of boric acid in a gas, oil, or electric furnace, using a plumbago crucible to hold the charge. Quick melting is desirable to avoid gassing of the melt. The temperature of the metal before pouring should be such that it may be poured at a rate approximating that at which the metal solidifies in the mold; otherwise blisters will be evident in the fabricated alloy. Zinc-sodium, phosphor-copper, and calcium boride have been used advantageously as deoxidizers to avoid these gas blisters. Such substances should be added in amounts small enough to leave little of the deoxidizer as a residue in the ingot; approximately 0.10-0.20% has proven sufficient in most cases.

The molds are prepared by preheating and coating with a dressing of grease and graphite, or a heavy vegetable oil. A vertical mold to give an ingot 8 in. x 3 in. x $\frac{1}{2}$ in. is suitable.

Fabrication—After pickling and cleaning, the ingots are broken down. This part of the process is an important step in the fabrication of white golds. Heavy reductions about 0.040-0.050 in. each pass, must be used to avoid splitting during subsequent annealing. Usually the ingot is reduced 50% before the first anneal. Insufficient reductions will almost without fail manifest themselves in splitting or "fire-cracking" on annealing. Alloys low in copper content will be more susceptible to this phenomenon. This technique applies equally well to the fabrication of tubing and wire as it does to sheet or strip.

Before annealing it is essential to have a uniform stress distribution in the metal bar or sheet; this may be accomplished reasonably well by passing through the last roll until absolutely flat. Annealing is carried out at from 710-760°C. Air cooling is used successfully. It is common practice to anneal in a nonoxidizing atmosphere or to protect the surface finish with an ochre-boric acid paint. Wire is generally protected by first dipping the coils in a hot saturated boric acid solution to coat them with a protective film.

Wear and Corrosion Resistance—The resistance to wear of the white gold jewelry alloys is more or less a function of the nickel content, and hence the hardness. It does, however, vary somewhat with the karat as well.

The corrosion and tarnish resistance of the alloys are governed mostly by the karat and to a certain extent by the base metal composition. The medium karats, such as 12 and 14, show good tarnish resistance in the presence of acids, body perspiration, and sulphur compounds. However, for continued use in contact with parts of the body the 12 karat alloys are often electroplated with a higher karat gold or rhodium. The 10 karat alloys, particularly those rich in copper, are quite susceptible to attack by sulphides and nitric acid.

The type of heat treatment to which the finished alloy has been subjected has marked influence on its resistance to corrosion and tarnish. It has been found that aged alloys are attacked more readily by corrosive agents, especially in the event that precipitated phases are more base than noble.*

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The Lead Industry

By F. E. Wormser*

History—Lead is one of the oldest metals known to man. Probably the earliest specimen is a figure found in the Temple of Osiris at Abydos and preserved in the British Museum. It dates from 3000 B.C.

The Pharaohs, Assyrians, and Babylonians had many uses for lead in ornamental objects and structural purposes.

In 2000 B.C. the Chinese made their first money of lead. In ancient Greece and Rome, bronze coinage contained 3-30% lead.

Perhaps the most interesting historical application of lead was its general use for water pipes by the Roman people. The pipe was made in 15 standard sizes and regular 10 ft. lengths. Many of these lead pipes, in almost perfect state of preservation, have been dug up in recent years in the ruins of Pompeii and Rome, and in England where the Romans penetrated during invasions. At Bath, England, there are old Roman baths using the same lead pipe installed by the Romans 1900 years ago. Roman lead pipe was made by folding heavy sheets of cast lead and burning the seams together.

Lead was often used for the construction of caskets beautifully decorated and inscribed. Many famous soldiers such as the Black Prince and Richard II, lie buried in leaden caskets. The resting place of Christopher Columbus in Santo Domingo is said to be a leaden casket.

Many magnificent buildings, erected in the 15th and 16th centuries, still stand under their original lead roofs. Leaden ornaments, statues, leader-heads and cisterns in a perfect state of preservation have been brought down to us today, many of them architectural gems.

Lead Minerals—Although at least 60 minerals containing lead are known to science, the lead of commerce is derived almost exclusively from one mineral, galena, the sulphide of lead. The oxides and other salts of lead are comparatively unimportant sources of supply. A list of common lead minerals follows: Galena, PbS ; cerussite, $PbCO_3$; anglesite, $PbSO_4$; crocoite, $PbCrO_4$; wulfenite, $PbMoO_4$; vanadinite, $3Pb_2(VO_4)_2 \cdot PbCl_2$; and pyromorphite, $3Pb_2(AsO_4)_2 \cdot PbCl_2$.

Lead Mining—Lead ore is mined in many countries, frequently in association with zinc ore. The United States is the most important source and contributes roughly one third of the annual world output. Then in order come Australia, Mexico, Canada, Germany, Spain and Burma. The British Empire produces about one quarter of the mined lead supply.

With the development of the flotation process for the treatment of complex lead-zinc ores, many mines are now productive where formerly it was impossible, or extremely difficult, to separate the lead and zinc from each other. The flotation process has revolutionized the concentration of lead ores, both simple and complex. It so happens that the principal lead mineral found all over the world is the sulphide galena, which lends itself especially well to treatment by flotation.

Smelting and Refining—Lead concentrates, when they leave the concentrating mill, contain upwards of 40% of lead, generally 60%. The concentrates are roasted to remove the sulphur and to agglomerate the fine flotation product which is not a physically desirable blast furnace material. The roasted sinter is charged into the top of a heated blast furnace, with suitable fluxes and coke and the resulting impure lead base bullion is shipped to the refinery for further treatment. It contains silver and gold and various impurities which have to be removed before the metal is suitable for use in industry.

In the United States the Parkes Process is widely used. Electrolytic refining is also practiced and a development of recent years, known as the Betterton Process, depending upon chlorination, has also been introduced into the United States.

The Parkes Process melts the impure lead and allows it to cool below the freezing point of copper, which crystallizes and is removed by skimming. It then passes to a reverberatory or softening furnace, where the temperature is raised and a blast of air oxidizes any antimony or arsenic present to form a skin which has to be removed. The lead then goes to desilverizing kettles where small amounts of

*Sec. Lead Industries Association New York.

zinc are added. As gold and silver have a greater affinity for zinc than for lead, these precious metals immediately leave the lead in favor of the zinc. The zinc being lighter than lead, rises to the surface and when the temperature is lowered, solidifies in a skin which is readily skimmed and subsequently treated to recover the precious metals.

Refined commercial lead of a purity of 99.99% lead is common. Pig lead is generally cast in bars weighing 80-100 lb. each. The ores of Southeastern Mo. contain too little silver for profitable desilverizing. Some of this ore contains a minute amount of copper, from 0.04-0.08%, which makes the resulting pig lead derived from it particularly desirable in the chemical industries, hence its designation as chemical lead.

Grades of Lead—Commercial grades of pig lead available to the consumer comprise: Corroding Lead, Common Lead, Chemical Lead and Antimonial Lead.

Corroding lead is the designation given to a premium grade of lead used by the "corroders" of white lead, who require a metal of exceptional purity so as to avoid discoloration of the resulting white lead.

Chemical Lead is so called because of its comparatively high resistance to corrosion by sulphuric acid and other chemicals. It finds its widest outlet in the chemical manufacturing industries. The term has been used for years to describe the undesilverized lead produced from Southeastern Mo. ores.

Antimonial Lead may contain anywhere from 1-25% antimony, with the average running between 6 and 7%. Antimonial Lead is used mainly by storage battery manufacturers.

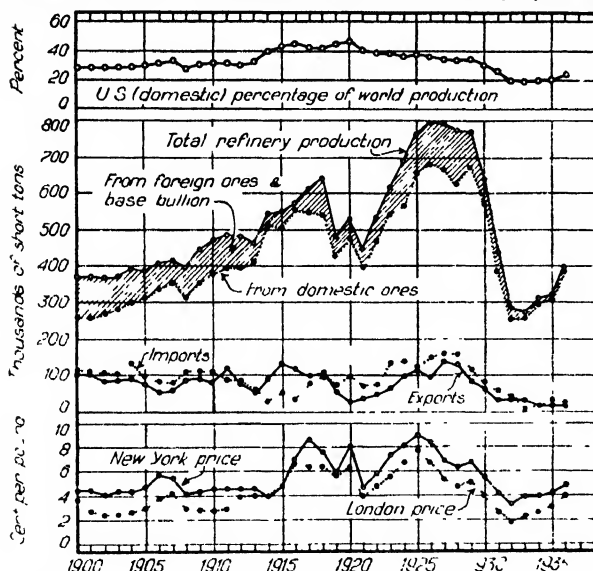


Fig 1.—Trends in the lead industry in the United States. Imports include lead in ore, base bullion, and refined lead, exports include refined lead (Bureau of Mines, Minerals Yearbook 1937).

batteries, but the use of lead for the manufacture of white lead was also extremely important. During the depression the production of white lead and other pigments have become more important as an outlet for newly mined pig lead than the electrical uses. The table on the following page shows a comparison between the uses of lead for 1929 and 1937.

The market for lead may be classified conveniently into (1) those applications where lead is used as a chemical compound and (2) those where it is used in the metallic form either alone or allied with some other metal.

The chemical compounds most important commercially are the hydrated basic lead carbonate, commonly known as white lead, basic lead sulphate (white and blue), litharge, red lead, the lead chromates, tetraethyl lead, and lead arsenate.

In the metallic form lead finds an important outlet in building construction as both pipe and sheet, and in solder. It is also used in important alloys such as type metal, antimonial lead for storage batteries, bearing alloys, foil and col-

The A.S.T.M. Specification B29-34T includes 3 grades of virgin pig lead: Grade I, corroding lead; Grade II, chemical lead; and Grade III, common lead.

Lead Industries—The following are the sellers of primary pig lead in the United States: American Metal Co., Ltd.; American Smelting & Refining Co.; Anaconda Sales Co.; Bunker Hill & Sullivan Mining & Concentrating Co.; Eagle-Picher Lead Co.; National Lead Co.; St. Joseph Lead Co.; and United States Smelting, Refining & Mining Co.

Uses of Lead—Before 1929 lead was principally used in electrical applications such as the manufacture of lead sheathed power and telephone cable and the manufacture of storage

lapsible tubes, as a coating for other materials, as lead weights, calking lead, gaskets, seals and in many other uses.

**Uses of Lead in the United States†
(In Short Tons)**

	1929	1937		1929	1937
White lead.....	119,700	86,000	Terne plate.....	4,200	6,400
Red lead and litharge.....	30,000	57,000	Foil	39,800	21,700
Storage batteries.....	210,000	192,000	Bearing metal.....	33,000	18,000
Cable covering.....	220,000	93,000	Solder	37,000	22,000
Building	96,000	45,000	Typemetal	18,000	17,000
Automobiles	18,000	12,000	Calking	31,500	15,000
Railway equipment.....	5,700	3,800	Castings	18,000	6,000
Shipbuilding	300	300	Other uses	50,000	50,000
Ammunition	41,100	39,500			
			Total	972,300	681,700

†American Bureau of Metal Statistics, includes virgin and scrap lead.

Basic Lead Carbonate—Basic lead carbonate is the most widely used of the lead pigments and forms the basis of the highest grade paint.

Basic Lead Sulphate—Basic lead sulphate is made directly from pig lead by a volatilization process in which the molten lead is fed through an atomizing flame in the presence of sulphur gases and air. The resulting fumed pigment is collected in bag houses.

Litharge—Litharge is a monoxide of lead (PbO) produced in powder and flake forms which contains roughly 93% lead and 7% oxygen.

Red Lead—Red lead is an oxide having the formula Pb_3O_4 and is made by heating powdered litharge under carefully controlled temperatures, lower than for the manufacture of litharge.

Sheet Lead—This useful metallic lead product is rolled in widths up to 11½ ft. wide and in any thicknesses desired. Sheet lead is widely used in chemical construction, where its resistance to attack from dilute sulphuric acid makes it a valuable metal to use in many industrial processes. It is also used in building construction as a roofing material, flashing, for shower pans, X-ray proofing and sound proofing.

Lead Pipe—Lead pipe has had a long career in transporting water and chemicals. It is a metal highly favored in the plumbing industry. Lead traps are another plumbing outlet.

Soldering Alloys—One of the commonest of the lead alloys is solder. Common solder contains 50% lead and 50% tin—the half and half grade. Another grade contains 60% lead and 40% tin and is used industrially for automobile radiators and the like. Plumbers' wiping solder carries 38-42% tin, 0-2% antimony, with the balance lead.

Hard Lead (Lead-Antimony Alloys)—This is an alloy containing from 1-12% antimony. Storage battery manufacturers use great quantities of antimonial lead containing approximately 7-12% antimony and frequently ¼% tin. Antimonial lead sheet (6% antimony), is also used widely in the United States for building construction. Hard lead is also used in shrapnel and collapsible tubes.

White Metal Bearing Alloys—White metal bearing alloys vary widely in composition. A common formula of a lead base bearing alloy used in railroad cars is 87% lead, 4% tin and 9% antimony. Lead bearing bronzes contain much smaller amounts of lead and are essentially mixtures of lead, copper and tin, with a lead content of 10-20%.

Numerous alloys of lead and alkaline earth, such as calcium and sodium have been developed in recent years and are playing an increasingly important part in bearing alloys.

Type Metals—This lead alloy is made from lead, tin and antimony. Typical composition is as follows:

Type Metals (In %)

	Lead	Tin	Antimony	Copper
Electrotype metal.....	93	3	4	.....
Linotype metal.....	85	3	12	.....
Monotype metal.....	87-84	3-4	10-12	.....
Stereotype metal.....	82-87	3-17	12-23	0-0.5
Type metal (small type).....	70	10	18	2

Fusible Lead Alloys—Many lead alloys are known which melt at low temperatures and which are used for electric fuses, automatic sprinkler systems and boiler plugs. Compositions will be found on page 1328 of this Handbook.

Terne Plate—Terne metal is an alloy of lead and tin used to coat black steel sheets. Terne alloy contains from 20-25% tin with the balance lead.

Lead Foil—Lead foil is generally known as composition metal foil and is made by rolling a sandwich of lead between 2 sheets of tin, the result being to produce a tight union of the metals. The composition foil used for wrapping cigarettes is generally 0.0005 in. thick.

Ammunition—Large quantities of lead are used in ammunition for both military and sporting purposes. The alloy used may contain up to 1% arsenic.

Lead Storage Batteries—Lead storage batteries furnish a large outlet for metallic lead and lead pigments. They consist of a series of plates made from antimonial lead and pasted with a mixture of litharge and red lead. The electrolyte used is sulphuric acid. The lead that is used for this purpose is generally reclaimed after the battery has ceased its useful life. During the depression lead reclaimed from old batteries became an important source of the metal, at times furnishing an amount of lead almost equivalent to that recovered from mining operations.

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Constitution of Lead-Antimony Alloys

By R. S. Dean*

The lead-antimony system so far as has been definitely shown may be represented by a comparatively simple constitutional diagram. Solid solutions are formed to the extent of a few per cent at both the lead and antimony ends of the system and these two solid solutions form a eutectic of about 12% antimony. Thermal and microscopic analyses do not show any evidence of an intermetallic compound. A general diagram of the system is shown in Fig. 1. The alloys near the lead end of the diagram are of greatest practical importance. The constitution diagram for this end of the system is reproduced on a much larger scale in Fig. 2. The solubility of antimony and lead decreases according to this diagram from 2.45% at the eutectic temperature to about 0.25% at 20°C. This decrease makes possible the dispersion hardening of the alloy by appropriate treatment. The essential points in this hardening are that the alloy be heated to a temperature above the solubility curve and cooled rapidly into the zone of supersaturation. The more rapid this cooling the more rapid the hardening takes place and the greater the final hardening. The agglomeration of the dispersed antimony, (or antimony-rich solid solution) takes place in this alloy at room temperature so that the maximum hardness obtained is not permanent, but falls off somewhat with time, approaching an equilibrium value for each temperature. This agglomeration of antimony particles is markedly accelerated by cold work on the alloy, thereby causing the hardened alloys to break down under fatigue to give widened grain boundaries in which the antimony is agglomerated to comparatively large particles.

A recent investigation by Obinata and Schmid using X-ray studies indicates that the solubility at 247°C. may be as high as 2.94%. According to these investigators the lattice constant falls linearly with increased atomic per cent of antimony from 4.9389 Å units for pure lead to 4.9371 Å units for the saturated solid solution. Studies by LeBlanc and Schöpel on the electrical conductivity of lead-antimony alloys, however, confirm the value of 2.5% antimony for the solubility limit at 249°C. The exact composition of the eutectic mixture has not been agreed upon. Unquestionably it depends upon the rate of cooling. By very slow cooling Quadrat and Jiriste find the value of 11.4-11.5% antimony for the eutectic. Alloys of eutectic composition were previously reported to expand on solidification. Fogler has shown this not to be the case. Heating curves show a eutectic temperature of

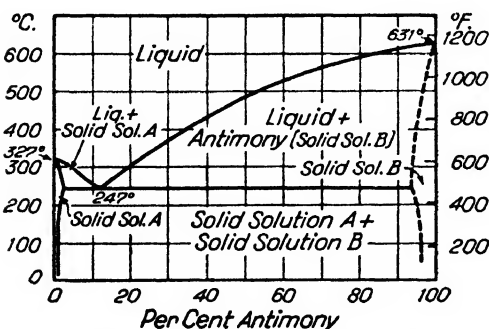


Fig. 1—Lead-Antimony Constitution Diagram (Gontermann, Dean, Schumacher, and Endo).

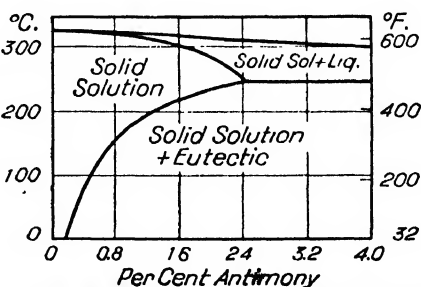


Fig. 2—Lead-Antimony Constitution Diagram for alloys of greatest practical importance

several degrees higher than cooling, doubtless due to the agglomeration of the antimony particles. Müller has studied the electrical conductivity in the liquid state and failed to find any evidence of a compound. Near the antimony end the investigations are somewhat meager. Endo studied the magnetic susceptibility and found a solid solubility of lead and antimony amounting to 5% at 250°C. LeBlanc

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and Schöpel found a solubility of lead in antimony of 3.5% at 249°C., by electrical conductivity measurement. This is not, however, confirmed by the X-ray studies of Solomon and Jones, who find that the lattice parameters of the antimony rhombohedra are identical in the pure metal and the hypereutectic antimony-lead alloys. The parameter of the lead lattice is changed, confirming the existence of solid solutions at the lead end of the system.

Hidnert has measured the thermal expansion of lead-antimony alloys from 2.9-98.0% antimony.

The earlier work on precipitation hardening in the lead-antimony system has been confirmed by H. Hanemann and his associates, who have also investigated the phenomenon of creep in these alloys. These investigators find an unusually large effect of the simultaneous presence of very small amounts of copper and arsenic on the hardness of the 1% antimony-lead alloy.

Ageew and Krotov have shown by X-ray analysis that the solid solution of antimony in lead is the simple monatomic type.

Derge, Kommel, and Mehl find that body-centered rhombohedral antimony precipitates from face-centered cubic lead as plates parallel to the [111] planes of lead.

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Constitution of Lead-Bismuth Alloys

By G. O. Hiers*

The lead-bismuth alloys form a eutectiferous system and no compounds exist. The alloys are mutually soluble in the liquid state and there are three solid solutions, designated as alpha, beta, and gamma.

The Liquidus—The liquidus curve has two branches, A B C and C D which meet at the eutectic, C, at 125°C. with a composition of 54.9% bismuth.

The Solidus—The solidus curve is defined as A E F G C H D. There is a peritectic point F at 184°C. with composition 29% bismuth. The peritectic horizontal E F B extends from E at 22.5% bismuth to B at 36.5% bismuth. The eutectic horizontal G C H runs from G at 36.7% bismuth to H at approximately 99.5% bismuth.

The remaining solid solution boundary points are I at 20% bismuth, J at 25% bismuth, K at 33% bismuth and L at about 0.1% bismuth, when considered at 0°C.

Due to recent knowledge, this diagram differs from the one in the International Critical Tables in several respects, namely:

1. The peritectic point and reaction horizontal are incorporated, representing the thermodynamic studies of Strickler and Seltz.
2. The eutectic point and horizontal limits are incorporated from the work of Strickler and Seltz.
3. The solid solution boundary points I, J and K are placed from X-ray studies of Solomon and Jones.

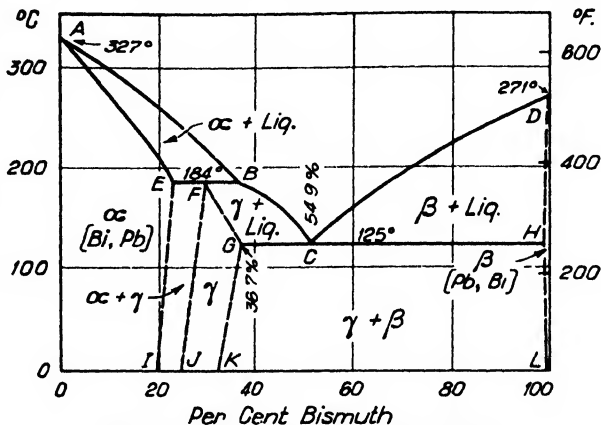


Fig. 1—Lead-bismuth constitution diagram.

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Constitution of Lead-Cadmium Alloys

By W. A. Cowan* and G. O. Hiers†

The lead-cadmium alloys have not been thoroughly examined with respect to equilibrium constitution, particularly with regard to the possible solid solutions which may exist. From the data known the two metals are completely soluble in each other when liquid, but only partially soluble when solid and form a simple eutectiferous series.

The Liquidus—The liquidus curve ABC descends rapidly to the eutectic point of 17.4% cadmium, existing at a temperature of 249°C. The liquidus BC which leads to the cadmium end of the diagram is rather extraordinary in shape and is taken from Kapp's cooling curve results. The eutectic point has been fixed by Barlow.

The Solidus—The solidus curve AD is dotted because there is no experimental

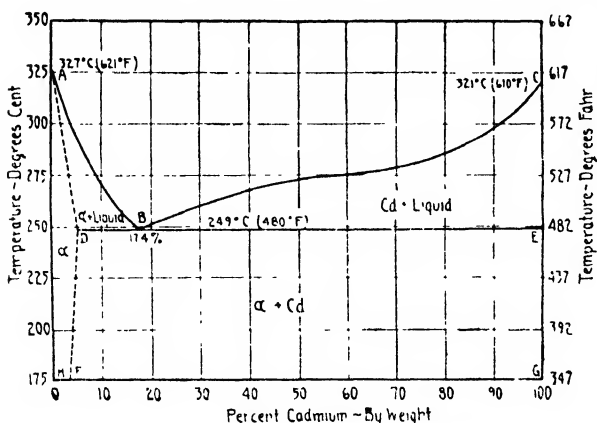


Fig. 1—Lead-cadmium constitution diagram.

vidence to determine its shape. The curve has been drawn straight leading from the melting point of lead at 327°C. to the eutectic arrest temperature horizontal. The point D is located by the Tammann method of measurement of the eutectic interval of time. Goebel also furnished further experimental evidence of such a composition by means of density and hardness measurements of specimens quenched from the eutectic temperature.

A dotted line DF has been arbitrarily drawn to indicate the limited solubility of cadmium in lead in the solid state. Vautin, in a British patent, indefinitely suggests 2% cadmium as the limit of solid solubility at ordinary temperatures.

Di Capera was unable to discover any evidence of the solid solubility of lead in cadmium and the eutectic arrest has been drawn to intersect the 100% cadmium vertical. Guertler considers the possibility of a maximum solubility of 8% lead in cadmium at the eutectic temperature.

The area ADB represents a mixture of liquid metal and the alpha solid solution, while CBE correspondingly shows a mixture of liquid metal and solid cadmium.

Alloys within ADFH consist entirely of alpha solid solution and DFGE denotes a heterogeneous mixture of alpha solid solution and solid cadmium.

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Constitution of Lead-Calcium Alloys

By Earle E. Schumacher* and G. M. Bouton*

A constitutional diagram for the system lead-calcium, constructed from thermal and microscopic data published by L. Donski¹ and N. Baar,² is given in Fig. 1. This

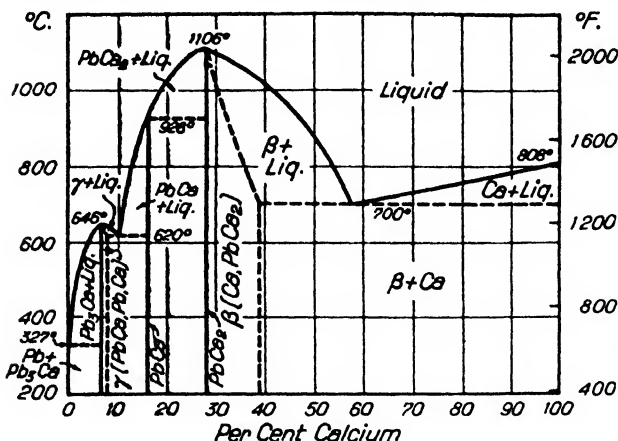


Fig. 1—Lead-Calcium Constitution Diagram (L. Donski and N. Baar).

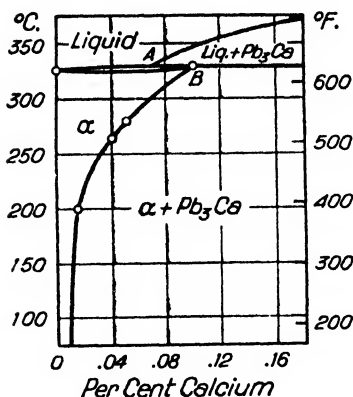


Fig. 2—Curves showing peritectic modification and solid solubility at the lead end of the lead-calcium diagram.

diagram shows the system to contain 3 compounds, Pb_3Ca , $PbCa$ and $PbCa_2$, which have freezing points at 646, 928 and 1106°C., respectively, and two eutectics, one at 10% calcium and one at 58% calcium. The compound Pb_3Ca is hard and brittle and not appreciably affected by exposure to the air. The other two compounds readily disintegrate in the air, especially if any moisture is present. The existence of these compounds has been confirmed by electrode potential measurements made by Kremann, Wostall and Schöpfer³ and by studies of the

pressure coefficients of electrical resistance made by W. C. Ufford.⁴ The eutectic at 10% calcium melts at 620°C. and consists of a solid solution ($PbCa$ in Pb_3Ca) and the compound $PbCa$. The eutectic at 58% calcium melts at 700°C. and consists of a solid solution (calcium in $PbCa_2$) and calcium.

Solid solutions exist between 6.1 and 7.6% calcium and between 27.6 and 39% calcium. No solid solutions have been reported in alloys at the extreme calcium end of the system. Recent investigations of lead-rich alloys show a peritectic reaction and a slight solid solubility of calcium in lead. In Fig. 2 is shown a constitution diagram for the lead end of the system, taken from the work of Schumacher and Bouton,⁵ and based on data from thermal analyses, microscopic examination, age hardening studies, and electrical conductivity measurements. The change in solubility from 0.1% calcium at 327°C. to 0.01% at 20°C. makes possible the dispersion hardening of certain of these alloys by appropriate heat treatment.

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Constitution of the Lead-Magnesium Alloys

By R. L. Dowdell* and Carrie H. Green*

Considerable work has been done on the simple lead-magnesium system. The earliest work reported on lead-magnesium is by Heycock and Neville.¹ The constitution diagram given by Hansen,² who has summarized the work well up to 1933, is shown in Fig. 1.

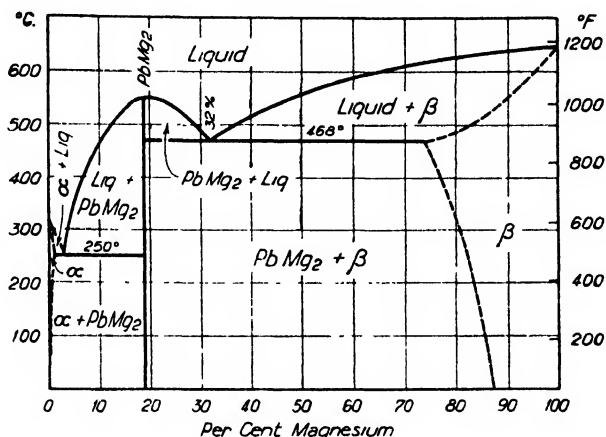


Fig. 1.—Lead-magnesium constitution diagram.

A summary of important data for this system is given in Table I.

Table I
Data on Constitution

	Investigators			
	Grube ³	Kurnakow and Stepanow ⁴	Abel Redlich Spausta ⁵	Lynn
Melting point, composition,				
PbMg ₂ (80.99% Pb).....	551°C.	550°C.		.. ..
Mg-PbMg ₂ eutectic temperature.....	459°C.	475°C.	470°C.	..
	average			
Mg-PbMg ₂ eutectic composition.....	67% Pb	68.05% Pb		.. ..
PbMg ₂ -Pb eutectic temperature	247°C.	253°C.	249°C	250°C.
	average	average		average
PbMg ₂ -Pb eutectic composition.....	97% Pb	97.8% Pb	.....	97.03% Pb
				Tammann's method
Max. solubility of Mg in Pb at eutectic temperature	(Kurnakow, Pogodin, Vindusova)			
		0.7% Mg		0.85% Mg
Max. solubility of Mg in Pb at room temperature (20°C.)		0.2% Mg		< 0.249% Mg*

*Cast alloy with 0.249% Mg age hardens at room temperature from 5.4 Vickers to 9 in about one month. When quenched from 240°C. after 1½ hours and aged for 90 hours at room temperature its hardness increased from 4.6 to 5.9. This indicates the solubility of magnesium in lead is probably less than 0.1%.

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Fig. 2 is an enlarged portion of the lead end of the lead-magnesium diagram by Lynn.

The compound Pb Mg_2 , (19% Mg by weight) resembles silicon in appearance on a fresh fracture, but on air exposure turns black rapidly and forms a fine black powder. The compound is exceedingly brittle and scratches glass easily. Its crystallographic structure was reported by Sacklowski,⁸ and later by Friauf,⁹ to be cubic (CaF_2 type) with a lattice parameter of 6.75 Å, with 4 molecules in the unit cell.

The effect of magnesium additions on the density of lead up to 5% magnesium is shown in Table II, together with some of their mechanical properties.

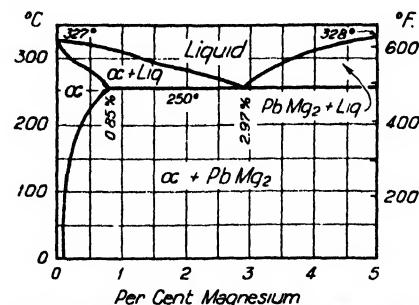


Fig. 2—Lead end of the lead-magnesium constitution diagram.

Table II
Density and Mechanical Properties of Lead-Magnesium Alloys

(Chill cast plates 0.125 in. thick)

Composition, % Pb*	Mg†	Calculated Density	Vickers Diamond Hardness 5 kg. load	Tensile Strength, psi.	Elongation, % for 1 in. Gage
100	0.0	11.34	4.1	1,970	64.0
99.90	0.10	11.30	7.0	3,580	21.0
99.75	0.25	11.11	13.3	4,950	14.0
99.50	0.50	11.07	15.5	5,940	10.0
99.25	0.75	10.91	17.1	6,920	11.0
99.00	1.00	10.75	18.5	7,045	10.0
98.00	2.00	10.23	18.6	7,950	8.0
97.50	2.50	10.0	18.9	11,340	12.6
97.00	3.00	9.75	19.0	.....	..
95.00	5.00	8.97	24.0	9,290	12

*Southeast Missouri desilverized commercial lead, purity, 99.997%.

†Magnesium of nominal purity, 99.9%.

Hanemann and Stockmeyer¹⁰ claimed that the addition of 1.0% magnesium hardened lead more than an addition of 14% antimony and that the alloy was stable in air and water and only slowly dissolved by acids. The writers,¹¹ however, find that a wrought alloy of even less than 1.0% magnesium decomposes rapidly in water, thereby dissociating water to hydrogen and hydroxyl ions. The small amount of eutectic of Mg_2Pb and alpha probably reacts galvanically with the result that the alloys fall apart even in distilled water, apparently by intergranular corrosion. Cast alloys are somewhat less active in decomposition.

Lead alloys containing 1-2% magnesium have been recommended for bird shot for waterfowl, primarily because of their fast decomposition in either water or gastric juices.

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Constitution of Lead-Silver Alloys

By A. J. Dornblatt*

Binary alloys of silver and lead form no intermediate phase, are miscible in all proportions when liquid, and on freezing form an eutectiferous series of alloys exhibiting but slight solubility in the solid state.

The complete miscibility of the two metals was established by Wright.¹ The liquidus curve was established through the work of Heycock and Neville,^{2,3} Friedrich,⁴ and Petrenko.⁵ These investigators placed the eutectic temperature at 304°C. The eutectic composition, according to Heycock and Neville, is 96% lead; according to Petrenko, about 97% lead, and, according to Friedrich, it is at 97.5% lead. This latter value is probably the most reliable. Yoldi and Jimenez, using micrographic and thermal analysis methods, verified the data of these earlier workers, locating the eutectic composition close to 97.7% lead and the eutectic temperature at 300-305°C.

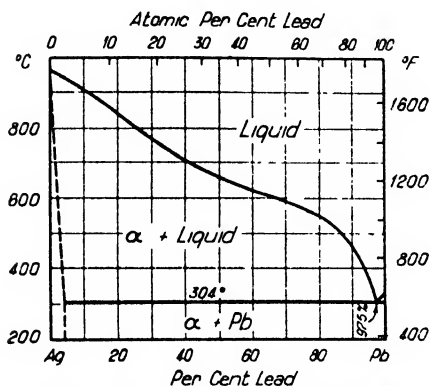


Fig. 1—Lead-silver constitution diagram.

diffusion and electrical conductivity studies. According to Seith and Keil, the limit of solid solubility is almost a linear curve falling from about 0.1% silver (.18 atomic per cent) at the eutectic temperature to about 0.05% silver (.09 atomic per cent) at 200°C. While not of value in determining exact solubility limits, the potential curves of Laurie¹⁰ and Puschin are of some interest.

The density of the alloys varies in a substantially linear fashion with the composition, according to the work of Matthiessen.¹¹ Spencer and John,¹² Stephens and Evans,¹³ Spencer and John as well as Stephens and Evans measured also the magnetic susceptibility of the alloy series. The effect of relatively small amounts of silver in raising the recrystallization temperature of cold worked lead was noted by Russell¹⁴ and in increasing the creep strength of lead was noted and discussed by both Russell¹⁵ and by Greenwood.¹⁶ Ludwik¹⁷ measured the hardness of several low-silver lead alloys. Fink and Pan¹⁸ demonstrated that alloys of this series were usefully resistant to anodic corrosion in brine solutions, the 61% silver alloy being recommended by them for this purpose. Tainton, Taylor, and Ehrlinger¹⁹ found that the addition of 0.5-1.0% of silver to lead anodes made possible the production of electrolytic zinc of much lower lead content than that obtained when pure lead anodes were used. Lead-silver solders containing small percentages of silver are described by Silberstein²⁰ and Johnson;²¹ the advantage of these solders is that they melt at a higher temperature than ordinary lead-tin solder.

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Constitution of Lead-Tin Alloys

By W. A. Cowan* and G. O. Hiers†

This is a eutectiferous system and there are solid solutions of tin in lead and lead in tin. The results of various investigators are contradictory in respect to further constituents which may exist. Future X-ray investigations may help to establish the diagram with finality.

The Liquidus—The liquidus curve ABC in Fig. 1 indicates a system with no compound and with the eutectic at 62% tin at a temperature of 183°C.

The lead branch of this curve AB is slightly concave for approximately half of its length and convex for the remainder. The tin branch BC is slightly concave to the lower region of the diagram.

The Solidus—The line AD represents the final solidification of the lead-rich end for alloys from 0-19.5% tin. This line is drawn from Stockdale's results.

The line DBE is the eutectic horizontal occurring at 183°C. All alloys from 19.5-97.4% tin become totally solid at this temperature. The line CE represents the solidus for alloys containing 0-2.6% lead, the maximum solid solubility determined by Jeffery.

Alloys of temperature and concentration shown in the area ADB will consist of crystals of solid solution alpha and liquid.

Alloys represented in the area CEB will contain crystals of the solid solution beta and liquid.

Changes in the Solid Alloys—The dotted curve DF shows the limit of solid solubility of tin in lead. It represents a compromise of determinations of Stockdale, and Parravano and Scortecchi. This solubility changes rapidly from 100-183°C.

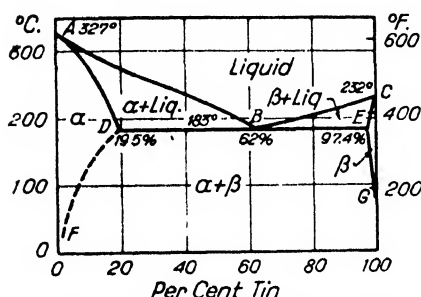


Fig 1—Lead-tin Constitution Diagram.

It may be noted that the solubility is 19.5% tin at 183°C., and drops to about 13% at 155°C. In alloys containing from about 18-62% tin, cooling curves in thermal studies of great sensitivity detect a slight exothermic point at approximately 155°C. In former diagrams this has been included as a horizontal line indicating a phase transformation. However, the experimental evidence may be construed as proving the change is not constitutional but merely due to supersaturation and a sudden precipitation permitted by the molecular mobility of the alloy.

Alloys in the indicated area ADF, when in equilibrium, consist entirely of solid solution alpha exhibiting a one-phase polygonal structure under the microscope. In practice, long annealings are necessary before complete equilibrium is established.

Beta is a solid solution of lead dissolved in tin and is represented by the indicated area CEG.

It may be noted that the lower limits of the solid solutions alpha and beta are not completely defined but undoubtedly will be in the future, with certainty.

Pure tin is noted for 3 allotropic forms: Gamma tin stable at 232-161°C.; beta tin stable at 161-18°C.; and alpha tin stable below 18°C. The influence of these transformations does not appear to justify the inclusion of such forms as phase change horizontals in the diagram, Fig. 1.

More thorough investigations may show such transformations in pure binary tin-lead alloys containing less than 10% lead.

X-Ray Evidence—Phebus and Blake studied lead-tin alloys by X-ray methods. They show a solid solution from 0-3.6% tin in lead, which corresponds to the face-centered cubic lattice of lead and varies in size from 4.942-4.931 Å. Alloys of 10-95% tin exhibit mixtures of the lead and tin lattice types.

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Alloys between 95-100% tin show the tetragonal lattice of pure tin, both in structure and size.

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Physical Constants of Lead

By James E. Harris*

Atomic Weight—The atomic weight of lead is 207.22. Lead is unique among the commonly occurring elements in that specimens have been found having atomic weights differing materially from the usually accepted value. These samples have in all cases been found associated with radioactive materials and have undoubtedly been formed by the radioactive disintegration of elements of higher atomic weights. Determination of the atomic weights of samples of lead from such sources by O. Honigsmid and coworkers and by T. W. Richards and coworkers have given values ranging from 206.046¹ to that of ordinary lead. Two determinations, those of Soddy and Hyman² and of O. Honigsmid³ give values higher than that of ordinary lead; namely, 208.4 and 207.92 respectively.

Atomic Number—The atomic number of lead is 82.

Isotopes—F. W. Aston⁴ has determined the percentages of abundance of the isotopes of lead as follows: 204 (1.5), 206 (28.3), 207 (20.1), 208 (50.1). J. L. Rose and R. K. Stranathan⁵ have made similar determinations as follows: 204 (0.8), 207 (21.4), 206 (26.3), 208 (51.5).

Allotropic Modifications—Cohen and Helderman⁶, Heller⁷, Janecke⁸, and others have come to the conclusion that lead exists in two allotropic modifications with a transition point at about 50°C. This conclusion is based in part on the fact that when lead is used as a cathode in a solution of lead acetate and nitric acid there are marked structural changes, the volume increasing slightly, the color changing to gray, the metal losing its malleability and firmness. Janecke by measuring the pressure-temperature cooling and heating curves found indications of a transition point between 59–62°C. Bridgman⁹ found no evidence of allotropy in his observations of the thermo-electric properties of lead. A. Thiel¹⁰ concludes that the results obtained by Heller, Cohen and others are due to chemical changes since the disintegration takes place only in the presence of nitric acid. Rawdon¹¹ could find no evidence for the existence of lead in allotropic modifications.

Density—The density at 20°C. of lead cast in vacuo is 11.3437 ± 0.0001^{12} . The density of solid lead at the melting point is 11.0¹³. The densities of molten lead at the temperatures indicated are given in Table I¹⁴.

Table I

Temp. °C.	Density	Temp. °C.	Density	Temp. °C.	Density	Temp. °C.	Density
331	10.663	416	10.558	555	10.382	694	10.219
345	10.642	459	10.507	577	10.360	717	10.200
356	10.632	486	10.475	580	10.354	731	10.188
411	10.583	529	10.423	650	10.265	...	.....

The density of molten lead at the melting point is found by extrapolation of the above data to be 10.667.

The density of lead derived from radioactive materials has been found to differ from that of ordinary lead in such a way as to make the atomic volume constant.

Compressibility—The compressibility of lead or percentage change in volume with unit change in pressure of one megabar is given by Richards and White¹⁵ at 25°C. between 100 and 500 megabars as 2.40×10^{-6} .

Crystal Form—Lead crystallizes in the face centered cubic lattice with the edge of length 4.9389 Å.¹⁶

Melting Point—The melting point of lead is $327.35^\circ\text{C.} \pm 0.05^{17}$.

Boiling Point—The boiling point of lead is variously given from 1525–1870°C. J. Johnston¹⁷ computes the boiling point from vapor pressure data at 1640 and Rodebush and Dixon¹⁸ at 1619°C. H. C. Greenwood¹⁹ and W. R. Mott²⁰ give 1525;

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Ruff and Bergdoll²¹, 1555; H. Von Wartenburg²², 1580 ± 20 ; P. Walden²³, 1700; and J. J. Van Laar²⁴, 1870°C. as the boiling point of lead.

H. C. Greenwood gives the boiling points at different pressures as follows:

Pressure in Atmospheres	0.14	0.35	1.0	6.3	11.7
Boiling Point °C.	1325	1410	1525	1873	2100

Critical Temperature and Pressure—J. J. Van Laar²⁴ estimates the critical temperature as 3000°C. and the critical pressure as 370 atmospheres. P. Walden²³ gives 3598 and W. Herz²⁵, 2696°C. as the critical temperature.

Heat of Fusion—Awbery and Griffiths²⁷ have found the heat of fusion of lead to be 6.26 cal. per g.

Heat of Vaporization—Rodebush and Dixon²⁷ give 223 cal. per g. for the heat of vaporization of lead.

Specific Heat

Specific heat²⁸ (mean) —180–20°C.....0.0300

Specific heat²⁸ (mean) 0–100°C.....0.03046

Naccari²⁹ gives the following values for the specific heats at the temperatures indicated:

°C.	15	50	100	150	200	250	300
Specific Heat	0.02993	0.03040	0.03108	0.03176	0.03243	0.03312	0.03380

Dixon and Rodebush³² give the following values in cal. per g. for the specific heats of liquid lead at the temperatures indicated:

°C.	365	378	418	459
Specific Heat	0.0335	0.0338	0.0335	0.0335

Thermal Conductivity of Lead—S. Konno³³ gives the following values for the thermal conductivity of lead. The values are given in cal. per cm. per sec.

°C.	0	100	200	400	500	600	700
Thermal Conductivity	0.063	0.081	0.077	0.038	0.037	0.036	0.036

Thermal Expansion of Lead

Linear coefficient of expansion³⁴ per °C. (mean) 10–100°C..... 29.5×10^{-6}

Linear coefficient of expansion³⁴ per °C. (mean) —190–19°C..... 26.5×10^{-6}

Cubical coefficient of expansion³⁴ at 20°C..... 85×10^{-6}

Electrical Resistivity and Temperature Coefficients of Resistance—Table II gives the electrical resistivities and temperature coefficients of resistance as determined by Pietenpol and Miley.³⁵ The temperature coefficients given are those defined by the equation:

$${}^{\circ}t_1 \quad t_2 = \frac{2(R_2 - R_1)}{(R_2 + R_1)(t_2 - t_1)}$$

The temperature coefficient of resistance as defined by the equation $R = R_1 + a_1(t - t_1)$ and calculated from the above data for the range 0–100°C. is 0.00406 as compared to the value of 0.00421 given by Bridgman³⁶.

For low temperatures H. K. Onnes and coworkers give the following figures, in values referred to the resistivity of lead at zero °C. as unity.

°C.	—103.61	—195.15	—216.61	—258.70
Electrical Resistivity	0.59548	0.25257	0.17129	0.01311

At the temperature of liquid helium, lead becomes a superconductor.

Table II

Temp. Range °C	a	Temp. °C	Resistivity Micro-ohms per cu. cm.
20-40	0.00336	20	20.648
40-60	0.00341	40	22.084
60-80	0.00335	60	23.645
80-100	0.00332	80	25.285
100-120	0.00311	100	27.021
120-140	0.00302	120	28.787
140-160	0.00299	140	30.582
160-180	0.00293	160	32.468
180-200	0.00291	180	34.413
200-220	0.00275	200	36.478
220-240	0.00273	220	38.542
240-260	0.00251	240	40.697
260-280	0.00246	260	42.791
280-300	0.00322	280	44.946
300-320	0.00665	300	47.938
320-330	0.0554	320	54.761
330-340	0.00116	330	96.735
340-360	0.000576	340	97.867
360-380	0.000570	360	99.000
380-400	0.000577	380	100.255
400-420	0.000561	400	101.418
420-440	0.000559	420	102.563
440-460	0.000558	440	103.716
.....	.....	460	104.878

Temperature Coefficient of Electrical Resistivity—The temperature coefficient of electrical resistivity of lead is given by Bridgman³⁰ for the range 0-100°C. as 0.00421.

Thermal Emf. of Different Elements Against Lead—The values for the constants in the equation $\frac{dE}{dt} = A + Bt$ are given in Table I. The thermo-electric powers at 20 and 50°C. and the neutral points are also given. The values given have been compiled by F. E. Fowle⁴⁰ from data presented by Becquerel, Mathiessen and Tait.

Electrode Potential—G. N. Lewis and T. B. Brighton give the normal electrode potential of lead against the normal calomel electrode as 0.4125 volt and against the normal hydrogen electrode as 0.1295 volt.⁴¹

Surface Tension—The following values from 327-500°C. are given by T. R. Hogness⁴² and from 750-1000°C. by Drath and Sauerwald⁴³. The values given are in dynes per cm.

°C.	327	400	500	750	900	1000
Surface Tension	444	438	431	423	401	397

Capillary Constant—Drath and Sauerwald⁴³ give the value 8.37 for the capillary constant.

Viscosity—The following values for the coefficient of viscosity of molten lead are given by R. Arpi⁴⁴. The values are in cgs. units.

°C.	340	376	419	470
Viscosity	0.0189	0.0167	0.0160	0.0144

Optical Properties—H. Von Wartenberg⁴⁵ gives for the index of refraction of lead for wave length 0.589μ the value 2.01; for the absorption index 3.48; and for the reflecting power 62%.

A. K. Aster⁴⁶ gives for the index of refraction of molten lead for a wave length of approximately 0.602μ the value 0.415 and for the absorption coefficient 1.76. Both were found to be constant over the temperature range 335-485°C.

Table III
The Thermoelectric Power of Lead Against Other Metals

Substance	A Micro- volts	B Micro- volts	Thermoelectric Power at Mean Temp. of Junctions (Microvolts)		Neutral Point
			20°C.	50°C.	
Aluminum	— 0.76	+ 0.0039	— 0.68	— 0.56	+ 195
Antimony, commercial pressed wire.....			+ 6.0		
Antimony, axial.....			+ 22.6		
Antimony, equatorial.....			+ 26.4		
Antimony, ordinary.....			+ 17.0		
Argentan.....	—11.94	—0.0506	— 12.95	— 14.47	— 236
Argentan.....				— 12.7	
Arsenic.....			— 13.56		
Bismuth, commercial pressed wire.....			— 97.0		
Bismuth, pure pressed wire.....			— 89.0		
Bismuth, crystal, axial.....			— 65.0		
Bismuth, crystal, equatorial.....			— 45.0		
Bismuth, commercial.....				— 39.9	
Cadmium.....	+ 2.63	+ 0.0424	+ 3.48	+ 4.75	— 62
Cadmium fused.....				+ 2.45	
Cobalt.....			— 22.		
Constantan.....				— 19.3	
Copper.....	+ 1.34	+ 0.0094	+ 1.52	+ 1.81	— 143
Copper commercial.....			+ 0.10		
Copper galvanoplastic.....			+ 3.8		
Gold.....			+ 1.2		
Gold.....	+ 2.80	+ 0.0101	+ 3.0	+ 3.30	(— 277)
Iron.....	+ 17.15	—0.0482	+ 16.2	+ 14.74	+ 358
Iron pianoforte wire.....			+ 17.5		
Iron commercial.....				+ 12.10	
Iron commercial.....				+ 9.10	
Lead.....		0.0000	— 0.00	0.00	
Magnesium.....	+ 2.22	—0.0094	+ 2.03	+ 1.75	+ 236
Mercury.....			— 0.413		
Mercury.....				— 3.30	
Nickel.....				— 15.50	
Nickel (—18-175°C.).....	—21.8	—0.0506	— 22.8	— 24.33	(— 431)
Nickel (250-300°C.).....	—83.57	+ 0.2384			
Nickel (above 340°C.).....	— 3.04	—0.0506			
Palladium.....	— 6.18	—0.0355	— 6.9	— 7.96	— 174
Palladium.....				— 6.9	
Phosphorus (red).....			+ 29.9		
Platinum.....			+ 0.9		
Platinum (hardened).....	+ 2.57	—0.0074	+ 2.42	+ 2.20	347
Platinum (malleable).....	— 0.60	—0.0109	— 0.818	— 1.15	— 55
Platinum wire.....				+ 0.94	
Platinum another specimen.....				— 2.14	
Platinum-Iridium alloys:					
85% Pt + 15% Ir.....	+ 7.90	+ 0.0062	+ 8.03	+ 8.21	(— 1274)
90% Pt + 10% Ir.....	+ 5.90	—0.0133	+ 5.63	+ 5.23	444
95% Pt + 5% Ir.....	+ 6.15	+ 0.0055	+ 6.26	+ 6.42	(— 1118)
Selenium.....			+ 807.		
Silver.....	+ 2.12	+ 0.0147	+ 2.41	+ 2.86	— 144
Silver (pure hard).....			+ 3.00		
Silver wire.....				+ 2.18	
Steel.....	+ 11.27	—0.0325	+ 10.62	+ 9.65	347
Tellurium.....			+ 502.		
Tellurium.....				+ 429.3	
Tellurium β			+ 500.		
Tellurium α			+ 160.		
Tin (commercial).....				+ 0.33	
Tin.....			+ 0.1		
Tin.....	— 0.43	+ 0.0055	— 0.33	— 0.16	78
Zinc.....	+ 2.32	+ 0.0238	+ 2.79	+ 3.51	— 98
Zinc pure pressed.....			+ 3.7		

Tensile Strength, Elongation, and Hardness—The following data are given by Hiers⁴⁷ for pure lead and two grades of commercial lead in the cast form.

	Southeastern Missouri Desilverized	Chemical Lead	Very Pure Lead
Yield point (0.5% elongation) (psi.).....	861	1643	714
Ultimate tensile strength (psi.).....	1966	2765	1609
Elongation (%).....	64.2	50.2	68.6
Reduction in area (%).....	92.4	87.9	100.0
Brinell hardness number 1 hr. after casting.....	4.2	5.5	2.9
Brinell hardness number 10 days after casting.....	4.1	5.4	3.0

Elastic Limit—Faust and Tammann¹⁰ have determined the elastic limit of lead by subjecting a highly polished specimen to a pull and observing microscopically the point at which the polish just begins to disappear. By this method the elastic limit of lead which had been melted and allowed to cool slowly was found to be 25 kg. per sq. cm. or 355 psi.

Young's Modulus—The values found for Young's modulus for lead vary from 1500-1900 kg. per sq. mm., 1800 per sq. mm., or 2.56×10^6 psi. may be taken as a representative value.

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The Properties of Lead-Antimony Alloys

By Earle E. Schumacher† and G. O. Hiers*

General—The constitution of lead-antimony alloys is given on page 1516 of this Handbook.¹ The features of greatest technical interest in lead-rich, lead-antimony alloys are those associated with "dispersion" or age hardening phenomena. Age hardening of these and similar alloys is brought about by heating them to a temperature above the solid solubility curve¹ and then cooling them rapidly to a temperature below this curve and aging. In general, the rate and degree of hardening become greater with increase in antimony content (up to the limit of solid solubility), with increase in concentration of impurities, and with increase in the rate of cooling.² The antimony, which is precipitated in a highly dispersed state by this treatment, gradually agglomerates during continued aging, even at room temperature, and the alloys eventually soften. The rates at which agglomeration and softening take place increase with increase in aging temperature (up to the solid solubility temperature) and are greatly increased by cold work.³

Microscopic, thermal, electrical resistivity, X-ray analyses and other evidence unite in confirming the above commonly held view of the nature of the lead-antimony system. However, thermodynamic considerations suggest other views. For instance, F. H. Jeffery⁴ postulates the formation of the compound Pb_3Sb , while Chu-Phay Yap⁵ believes the evidence necessitates the presence of Sb_2 in solid solution.

Lead-antimony alloys containing from 0.5-1.0% antimony are extensively used as cable sheathing materials.⁶ In the United States, almost all telephone cables are sheathed with a lead-1% antimony alloy. Since this alloy has been so extensively used, it has naturally been carefully studied and a large amount of data collected. It is desirable, therefore, to consider some of the properties of this alloy separately.

Properties of 1% Antimony-Lead Alloy

Electrical Conductivity—The resistivity at 0°C. of supersaturated solid solutions of lead-antimony alloys containing from 0.4-1.1% antimony has been determined by Schumacher and Ferguson.⁶ Under these conditions, the resistivity of lead-1% antimony alloy is 2.415 ohms per m.g. The conductivity of various lead-antimony alloys in equilibrium at 25°C. has been determined by Schumacher and Bouton.⁷ The lead-1% antimony alloy has a conductivity of 45,350 mhos per cm.

Corrosion—The corrosion of lead-1% antimony under different conditions has been studied by Burns and Freed,⁸ and others.^{9,10} Burns and his co-workers¹⁰ developed an electrical resistance method of measuring the corrosion of lead by acid vapors and by this method found that the corrosion of lead-1% antimony in creosoted wood ducts is definitely associated with the presence of acetic acid vapor, oxygen, and carbon dioxide.

Grain Growth—The growth of grains in lead-1% antimony alloy has been studied by Dean and Hudson,¹¹ who report that crystal growth of this material proceeds with a velocity proportional at any instant to the difference between the ultimate volume and the mean crystal volume at that instant. These workers also found that the ultimate or equilibrium volume of the crystals is an exponential function of the temperature and a linear function of the amount of working as measured by the decrease in height of a cylindrical slug.

Effect of Impurities—The effect of impurities contained in a lead-1% antimony alloy on the rate and extent of its aging has been studied by Schumacher, Bouton, and Ferguson.¹² Most impurities, and especially arsenic, greatly increase the rate and extent of age hardening.

Lattice Parameter—X-ray investigations of Obinata and Schmid¹³ indicate that the lattice parameter of pure lead ($a = 4.9389\text{\AA}$) is reduced by 0.01% by the presence in solid solution of 1 atomic per cent antimony.

Mechanical Properties—Extruded cable sheath made of Grade II A.S.T.M. lead and containing 1% antimony has the following properties when cooled slowly and aged one month at room temperature:

Tensile Strength—2750-3050 psi. as measured on tensile specimens having a reduced section 3 in. long, $\frac{1}{2}$ in. wide, and $\frac{1}{4}$ in. thick and pulled at the rate of $\frac{1}{4}$ in. per in. of free length per minute.

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Elongation—30-40% in 2 in. of specimen length across the break.

Rockwell Hardness—30-45 on the S.M. No. 30 scale. (This is a special soft metal scale used for comparing the hardness of various lead cable sheath alloys. The scale employs a 30 kg. load, a $\frac{1}{4}$ in. dia. ball penetrator, and a 2 in. dia. ball anvil. The major load is applied for 1 min. Readings are made from the red figures on the dial.)

Endurance Limit—800 psi. (50,000,000 cycles at 700 per min.) (Determined with specimens of the type described by J. R. Townsend¹⁴ and tested on a machine described by C. H. Greenall.¹⁵)

Aging Strength—Quenching this alloy from 250°C. produces a tensile strength of about 2,800 psi. which subsequently increases to about 6,000 psi. as a result of

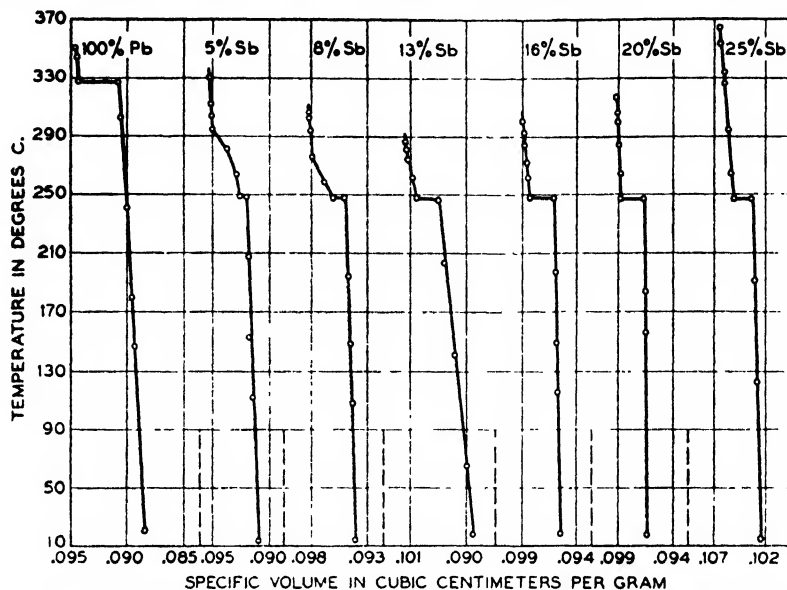


Fig. 1—Solidification shrinkage and change in volume with temperature of lead-antimony alloys.

aging at room temperature. Cable sheath which cools slowly from 250°C. does not undergo this wide variation in strength.

General Discussion of Lead-Rich Alloys

Casting Properties and Thermal Coefficient of Expansion—Lead-antimony alloys containing from 7-12% antimony have good casting properties and comparatively high strength. For use as automobile storage battery grids, however, which have a lattice structure of fine ribs, it is customary to add about 0.25% tin to improve the casting quality. Die castings are often made of 10% antimony-lead. Goodrich¹⁶ determined the solidification shrinkage and volume changes of several lead-antimony alloys ranging from 0-25% in antimony content. These data are plotted in Fig. 1. The expansivity coefficient of cast lead-antimony alloys containing from 0-15% antimony as given by Vinal¹⁷ is shown in Table I. For extruded lead, Hiers¹⁸ found the coefficient of linear expansion in the range 25-185°C. to be 0.000029 per °C., and for extruded 6% antimony-lead, he found 0.000027 per °C.

Electrical Conductivity—The conductivities of various extruded lead-antimony alloy wires are given by Dean, Zickrick, and Nix¹⁹ for different aging treatments. Fig. 2 contains curves, plotted from their data, showing the conductivities of these wires, in terms of pure lead, as heat treated at 235°C. and quenched, and as heat treated, quenched, and aged at room temperature for 125 days.

The resistivities at 20°C. of lead-antimony alloys containing from 0-16% antimony given by Vinal¹⁷ are reproduced in Table I. Data on the resistivity of alloys containing up to 70% antimony published by Matthiessen²⁰ are given in Table II as they appear in the International Critical Tables.²¹

Thermal Conductivity—Data given in the International Critical Tables²⁷ on the thermal conductivity of lead-antimony alloys are plotted in Fig. 3.

Density—The density of various lead-antimony alloys as determined by Goebel²⁸ from cast specimens are shown plotted in Fig. 4. Vinal's²⁹ data on density are given in Table I.

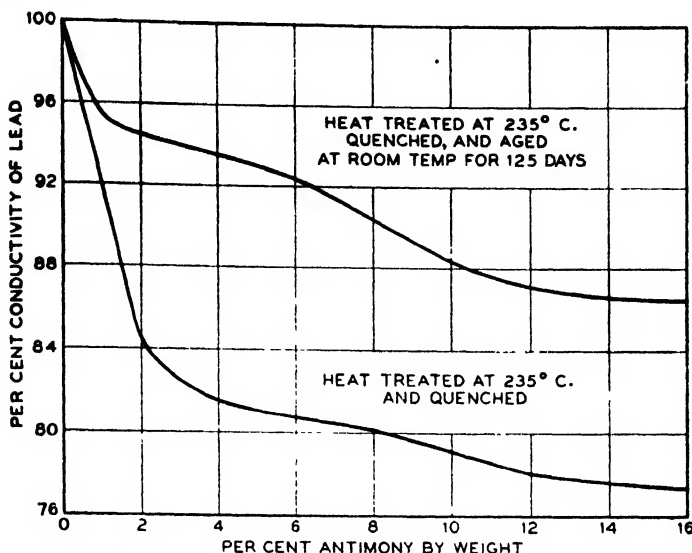


Fig. 2—Conductivity of extruded lead-antimony wires at 20°C.

Specific Heat—The results of tests by Durrer³⁰ and by Linnavuori³¹ show that, at any constant temperature, within the temperature range of 20-100°C. the specific heat of lead-antimony alloys is a linear function of composition. (Average values of specific heat, in cal. per g. of antimony and lead within the temperature range 20-100°C. are: Lead = 0.0305; Antimony = 0.0508.)

Thermoelectric Power—According to Pelabon³², alloys having a eutectic structure usually have a higher thermoelectric power than that given by the mixtures rule. For lead-antimony, the actual values of emf. against platinum at 100°C. are given in Table V along with values calculated from the mixtures rule. Rudolf³³ also gives data on the thermoelectric power of lead-antimony alloys.

Mechanical Properties—Values of tensile strength, elongation, and Brinell hardness of commercial 4%, 6%, and 8% antimony-lead rolled sheet as reported by Hiers^{34, 35} are listed in Table III. This table gives values for the sheet as aged for various periods at room temperature after rolling, and as aged at room temperature after being quenched from a temperature of 235°C. The alloys tested were small samples cut from sheets rolled to a thickness of $\frac{1}{8}$ in. from a cast slab about 3 in. thick. Tensile strength, elongation, and hardness data given by Vinal³⁶ for cast lead-antimony alloys are shown in Table I. Both Hiers' and Vinal's tensile strength data are plotted in Fig. 5.

Brinell hardness data given by Goebel³⁷ for a series of alloys are shown in Table I (a).

Table I (b) contains data on tensile strength, elongation, and Brinell hardness for a series of alloys extruded as $\frac{1}{4}$ in. dia. rod and aged approximately two weeks at room temperature. The tensile specimens were 14 in. long with a reduced section 8 in. long by $\frac{1}{4}$ in. in dia. and were pulled at the (gross) rate of $\frac{1}{4}$ in. per min. Elongation was measured in two in. of original specimen length including the break. The Brinell tests were made with a 300 kg. load applied to a 10 mm. ball for 30 seconds.

The tensile strength of a series of lead-antimony alloys in the form of extruded wires given various heat and aging treatments has been published by Dean, Zickrick, and Nix.³⁸ Some of these data representative of a more or less standard condition of the alloy are shown in Fig. 6.

The fiber stresses which can be withstood for indefinitely long periods at various temperatures by extruded pipe composed of "chemical" lead and of 6% antimony-

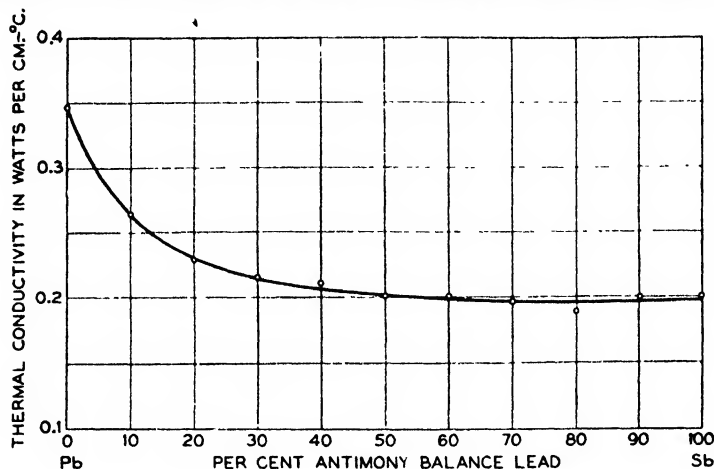


Fig. 3—Thermal conductivity of lead-antimony alloys.

lead alloy have been published by the Lead Industries Association²⁸ and are reproduced in Table IV.

Welding and Soldering—Lead-antimony alloys can be welded by gas torches and other suitable heating appliances and they can be soldered by many alloys such as the lead-tin or lead-tin-cadmium eutectics. For material used in corrosive atmos-

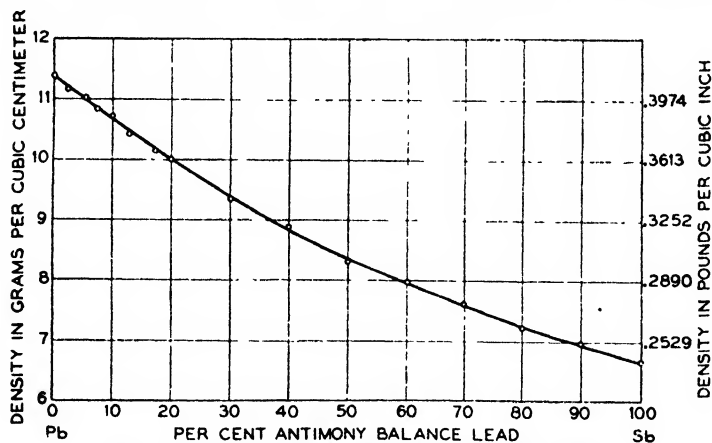


Fig. 4—Density of lead-antimony alloys at 18°C. ± 2°C.

pheres, it is advisable that the alloy used for making the joint be of approximately the same chemical composition as the parts joined.

Bearing Alloys—Antimonial lead was one of the early lead-base bearing alloys used with satisfactory results. An alloy containing 10-12% antimony is commonly known as Standard No. 4 Babbitt metal. This alloy has excellent casting properties and can be used satisfactorily for bearings in slow moving machinery. The A.S.T.M. Standards, B23-26, lists two lead-antimony alloys and their properties as follows:

No.	Sb	Composition, %			Ultimate Strength in Compression, Pst.		Brinell Hardness No.		Pouring Temp., °F.
		Pb	Cu	As	68°F.	212°F.	68°F.	292°F.	
11	15	85	0.50 max.	0.20	12,800	5,100	15.0	7.0	630
12	10	90	0.50 max.	0.20	12,900	5,100	14.5	6.5	625

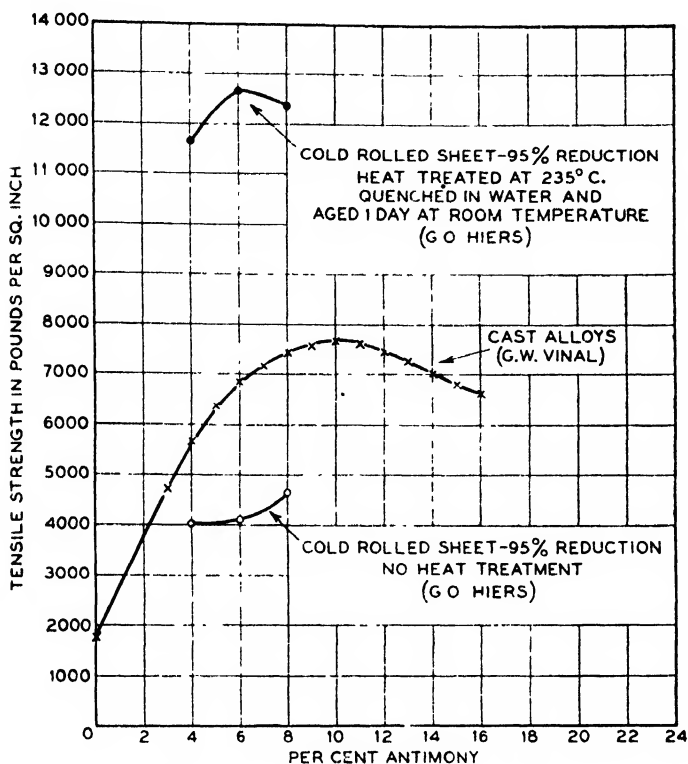


Fig. 5—Tensile strength of lead-antimony alloys.

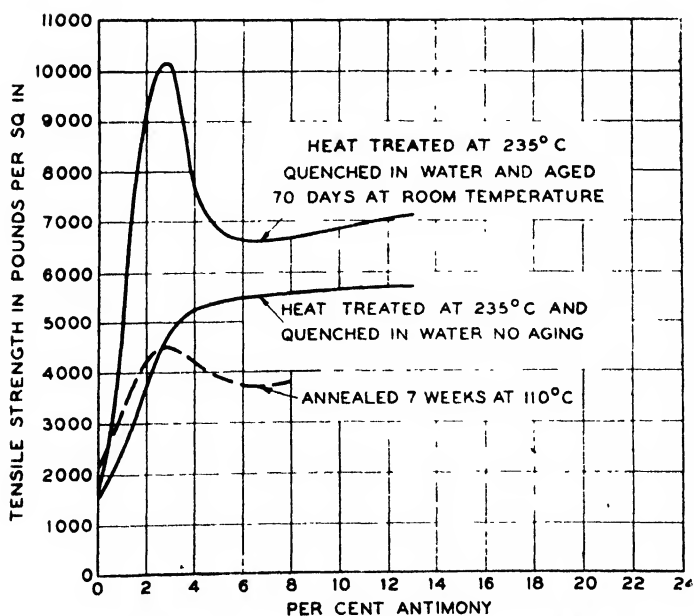


Fig. 6—Tensile strength of extruded lead-antimony wires.

Corrosion Resistance—Lead-antimony castings containing up to 12% antimony have sufficient corrosion resistance combined with their mechanical strength to find considerable use in the chemical industry in machinery and apparatus. In some instances, particularly where chemical solutions would tend to deposit copper on lead by galvanic action, serious corrosion and pitting can be avoided to a considerable extent by the substitution of lead-antimony alloys for lead. This beneficial effect of antimony in lead is probably due to its position in the electrochemical series.

Table I
Properties of Cast Lead-Antimony Alloys

Antimony, %	Density	Tensile Strength, psi.	Elongation, %	Hardness, Brinell No.	Expansivity Coefficient	Resistivity 20°C., ohm-cm.
0	11.33	1780	..	3.0	0.0000292	0.0000212
1	11.26	....	..	4.2	0.0000288	0.0000220
2	11.18	....	..	4.8	0.0000284	0.0000227
3	11.10	4700	15	5.3	0.0000281	0.0000234
4	11.03	5660	22	5.7	0.0000278	0.0000240
5	10.95	6360	29	6.2	0.0000275	0.0000246
6	10.88	6840	24	6.5	0.0000272	0.0000253
7	10.81	7180	21	6.8	0.0000270	0.0000259
8	10.74	7420	19	7.0	0.0000267	0.0000265
9	10.66	7580	17	7.2	0.0000264	0.0000271
10	10.59	7670	15	7.3	0.0000261	0.0000277
11	10.52	7620	13	7.4	0.0000258	0.0000283
12	10.45	7480	12	7.4	0.0000256	0.0000289
13	10.38	7280	10	..	0.0000253	0.0000293
14	10.30	7000	9	..	0.0000251	0.0000293
15	10.23	6800	8	..	0.0000248	0.0000292
16	.....	6620	8	..	.....	.....

Table I (a)
Brinell Hardness of Chill Cast Antimonial Lead

Antimony, %	0	2.5	7.5	13	17.5	30	40	60	70	90	100
Brinell No., 20 kg. load, 4 mm. ball, 20 sec.	4.1	8.5	13.0	16.5	16.5	18.8	19.7	21.4	25.0	31.0	25.9

Table I (b)
Mechanical Properties of Extruded Lead-Antimony Rod

Composition % Antimony	Ultimate Tensile Strength, psi.	% Elongation, in 2 in.	Brinell No.
0	1740	110	2.0
1	2920	58	5.1
2	3200	56	6.5
3	3100	55	7.7
4	3100	58	8.9
5	3150	59	9.9
6	3300	65	10.7
7	3240	68	11.4
8	3330	75	12.4
9	3400	76	12.8
10	3700	64	13.7
11	3800	74	13.7
12	3800	65	14.3
13	4000	57	14.6
14	3930	48	14.6
15	4180	41	14.9
16	4110	36	14.9
17	4180	34	14.9
18	4340	22	15.3
19	4380	29	15.3
20	4460	23	15.9

Microscopic Examination—Methods of preparing lead-antimony and other lead-rich alloys for microscopic examination have been described by Lucas¹⁴, Schumacher and Bouton¹⁷, Bassett and Snyder¹⁸, Vilella¹⁹, and others. A rapid, efficient, and frequently used method consists of simple microtoming followed by an etch with a solution of 1 part of 30% hydrogen peroxide to 3 parts of glacial acetic acid.

Table II
Resistivity of Lead-Antimony Alloys

Antimony, %	Temp., °C.	Resistivity in microhm-cm.	Antimony, %	Temp., °C.	Resistivity in microhm-cm.
2.31	23.7	21.7	23.05	24.1	32.6
5.63	25.6	23.2	37.1	23.4	39.2
10.56	25.4	25.55	54.1	26.3	46.5
16.45	26.1	27.9	70.3	24.2	53.9

Table III
Mechanical Properties of Commercial Cold Rolled (95% Reduction)
Antimonial Lead Sheet

Ultimate Tensile Strength, psi.			Per Cent Elongation		
As Cold Rolled	1 Day After Heat Treatment†		As Cold Rolled	1 Day After Heat Treatment†	
4% Sb .....4,020	11,670		48.5	6.3	
6% Sb .....4,100	12,650		47.0	3.2	
8% Sb .....4,650	12,350		31.3	4.7	
†Heat treated at 235°C., quenched, and aged 1 day at room temperature.					
Brinell Hardness $\frac{1}{16}$ in. Ball 9.85 kg. Load for 30 sec.					
Length of Aging Period at Room Temp.	1 Day	4 Days	14 Days	104 Days	7½ Years
4% Sb aged without heat treatment.....	8.1	...	...	8.6	8.3
4% Sb heat treated† and aged.....	24.3	24.3	22.0	22.8	18.4
6% Sb aged without heat treatment.....	8.6	...	...	9.0	9.0
6% Sb heat treated† and aged.....	23.5	26.0	23.1	21.2	17.4
8% Sb aged without heat treatment.....	9.5	...	...	10.1	10.0
8% Sb heat treated† and aged.....	26.3	26.5	25.3	24.0	19.9
†Heat treated at 235°C., quenched, and aged 1 day at room temperature.					

Table IV
Allowable Fiber Stress in Extruded Pipe, psi.

Temperature, °C.	"Chemical" Lead	6% Antimony-Lead	Temperature, °C.	"Chemical" Lead	6% Antimony-Lead
20	200	400	90	136	195
30	190	370	100	127	165
40	180	340	110	118	137
50	172	310	120	110	110
60	162	280	130	100	80
70	153	254	140	90	50
80	144	222	150	80	...

Table V
Thermoelectric Power

Antimony, %	Actual emf. of Lead-Antimony Alloy against Platinum micro-volts per °C.	Calculated emf. of Lead-Antimony Alloy against Platinum (From Mixtures Rule) micro-volts per °C.
0	5.14
20	9.27	14.94
40	11.43	24.73
60	13.97	35.52
80	27.92	44.32
100	54.12	

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Properties of Lead-Calcium Alloys

By Earle E. Schumacher* and G. M. Bouton*

General—The constitutional diagram for the lead-calcium system is given on page 1520 of this Handbook. The alloys of greatest interest are those containing between 0.01% and 0.1% of calcium. Because they are age hardening, the properties may be markedly affected by the methods used in the preparation of specimens for test. Also, as is true with most other lead-rich alloys, the values obtained on tests may be strongly influenced by the manner in which the tests are conducted.

Effect of Heat Treatment on Hardness—The usual precipitation hardening procedures are applicable to lead-calcium alloys. Precipitated calcium goes into solution in a few minutes at temperatures above the solid solubility curve. Once in solution, either as a result of heat treatment or cooling from the molten state, the calcium does not precipitate rapidly from unworked alloys containing about 0.03-0.04% of calcium until the temperature falls to below approximately 200°C. This makes it possible to extrude these alloys below the solid solubility temperatures without sacrifice in hardening possibilities. It is possible to control the hardening potentialities of the alloys by precasting them, allowing them to age at room temperature for a short while to permit precipitation to start, and then, heating to and extruding at some temperature below the solubility curve. The strength attainable on aging materials produced in this latter manner is a function of the extrusion temperature.

The rate of cooling the lead-calcium alloys, after the solution heat treatment, is critical with respect to the rate at which hardening occurs during subsequent aging at room temperature, but is not critical with respect to the maximum hardness eventually attained even though the time to cool varies from a fraction of a second to several hours.

The age hardening characteristics of the alloys are interesting. Aging quenched specimens at room temperature results in a rapid initial rate of hardening followed by a slow but continued increase of hardness for a few years. Aging at 100°C. immediately after cooling to room temperature does not produce as great hardness as room temperature aging. If, however, the quenched alloys are allowed to age at room temperature for a period of time varying from a few days for the 0.1% calcium alloy to a few months for a 0.03% calcium alloy, heating for about a day at 100°C. produces an increase in hardness (or strength) to the maximum obtainable for the particular material. At temperatures between 75°C. and the solid solubility line the alloys over age. The degree of over aging depends upon the duration of the heat treatment and the temperature. This serves as one method of controlling the strength and stabilizing the alloy.

Tensile Properties—Curve 1 in Fig. 1 shows the maximum tensile strengths attainable in lead-calcium alloys by room temperature aging following solution heat treatment and quenching. Curve 2 shows the strengths determined immediately after quenching. Curve 3 shows the strengths of alloys cast in a hot mold, air cooled, and then aged 7 days at room temperature plus 16 hrs. at 100°C. This illustrates that rapid quenching is not essential and that the secondary 100°C. aging is effective in developing maximum strength in lead-calcium alloys. It is, of course, possible to stabilize tensile strength at values between those for the quenched, and those of the quenched and aged material by control of the manufacturing conditions, and by appropriate heat treatment.

Creep Properties—All investigators have reported that the lead-calcium alloys have high creep resistance. The results of tests conducted by Moore, Betty, and Dollins² on samples cut from flattened cable sheath are given in Fig. 2 and 3. While the absolute values of creep are greatly influenced by the exact history and

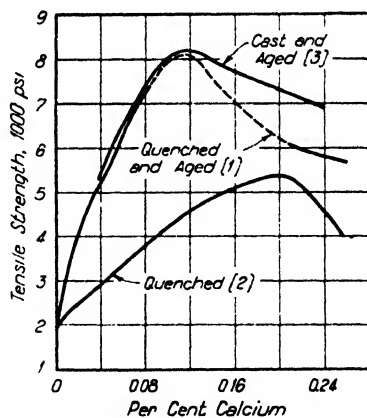


Fig. 1—Tensile strength of lead-calcium alloys.

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purity of the materials, these results are typical, and illustrate the degree of superiority of lead-calcium alloys over other lead-rich alloys.

Fatigue Properties—The endurance limits of lead and lead-rich alloys are given in Table I. The wide diversity of test methods and preparation procedures used by the various investigators precludes direct comparisons. However, each set of data shows lead-calcium alloys to be decidedly superior to pure lead, and it is worthy of note that no investigator has reported a lead-rich alloy having a higher endurance limit than can be obtained with lead-calcium alloys.

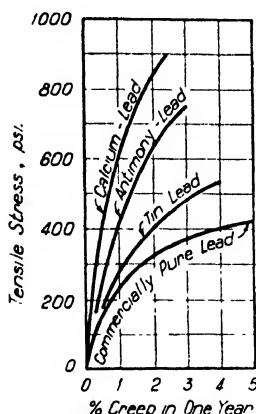


Fig. 2—Comparative creep of lead-calcium cable sheath materials at room temperature.

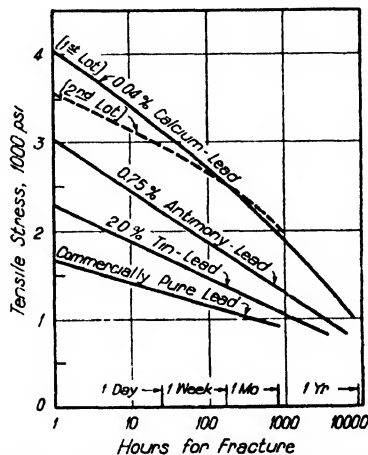


Fig. 3—Failure of lead-calcium alloys under steady load.

Table I
Fatigue Data

Investigators	Material	Endurance limit at 5×10^7 cycles, psi	Preparation of Sample and Method of Test
H. F. Moore et al. ^{1,2}	Pb Pb-0.04% Ca Pb-1% Sb	400 1,000 1,000	Samples cut from flattened cable sheath and tested as cantilever beams.
R. S. Dean & J. E. Ryjord ³	Pb-0.04% Ca Pb-0.04% Ca	1,200 1,500	
E. E. Schumacher ¹ & G. M. Bouton	Pb Pb-1% Sb Pb-0.04% Ca Pb-0.06% Ca	< 250 500 820-1,020 1,120	
J. R. Townsend ³ & C. H. Greenall	Pb Pb-1% Sb Pb-0.038% Ca	215 300-450 685-840	
		Endurance limit at 10^7 cycles, psi.	
H. Waterhouse ⁴	Pb Pb-0.026% Ca Pb-0.041% Ca	470 1,038 1,180	Samples machined from 1 in. dia. round rod extruded from 1 1/2 in. dia. slugs. Tested in tension and compression along axes of specimens.

Chemical Analysis—The accurate determination of such small quantities of calcium as are used in these alloys requires a special technique. A rapid, high-precision method⁵ is available.

Uses and Special Properties—The alloys containing 0.025-0.04% calcium possess properties which make them attractive for use as telephone and power cable sheathing. For these applications, extensive, but as yet incomplete, appraisal studies have been conducted over some years. Alloys containing 0.045-0.1% calcium possess properties which make them of interest for storage battery applications.^{6,7} Anodically and cathodically, the behavior of lead-calcium alloys containing up to 0.1% calcium is similar to that of pure lead. The rate of sulphation of storage battery elements

made of lead-0.1% calcium alloy is about one-tenth that of elements made from the present standard lead-9% antimony alloy.

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Properties of Lead-Tin Alloys

By George O. Hiers*

Lead-tin alloys are used in large quantities because, among other reasons, of the ease in melting and applying to other metals in the forms of solders or coatings. Since all of the alloys throughout the entire system are readily workable, they can be rolled, extruded, swaged, and stamped, even in the cold state. The corrosion resistance of the alloys is noteworthy and important, particularly when they are used as foil and coatings such as terne and tin plate. The principal uses of the alloys may be classified approximately as follows:

% Tin,
Balance Lead

-
- | | |
|-------------|--|
| 1-3..... | Lead foil; for electrical condensers, electrical fuses, wrapping tea, bottle caps, for covering stems of cut flowers. Cable sheathing; for coverings of electrical telephone, telegraph, and power cables. |
| 3-8..... | Hot dip coatings on sheet iron or on sheet copper for roofing. Solders of the highest melting range in the system Pb-Sn. Rolled sheet and extruded pipe for tank linings, anodes, and heat transfer coils in chromium plating tanks. |
| 15-25..... | Coating sheet iron by hot dipping (terne plate). Tobacco foil. Low grade solders. |
| 25-60..... | Solders. |
| 85-100..... | Coating various metals by hot dipping. Final products; sheet "tin" or tinned iron or tin plate, "tin" cans tin lined or coated copper utensils. Tin foil. Collapsible tubes. In the U.S.A. only pure tin coatings or metal are permitted for use in contact with foodstuffs. |
-

Density—Goebel¹ determined the density values for the solid alloys (Fig. 1), while Goodrich² obtained values for the liquid metal. Goodrich also determined solidification shrinkages. These data are given in Fig. 2 and 3. A change in state of beta to alpha allotropic forms occurs with pure tin at and below 18°C. "Tin disease" is a disintegration of the metal due to the density change of 7.29-5.85 accompanying the allotropic change. It is practically unknown in the Pb-Sn alloy system where lead is present in amounts of over 10%. Tammann describes lead as an inhibitor of "tin disease." The allotropic change from gamma to beta tin at 161°C. is also accompanied by a volume change shown in Fig. 3.

Tensile Properties—Values for tensile strength and elongation of the cast alloys, as determined by several investigators, are shown in Fig. 4. Other strength characteristics at elevated temperature are shown in Fig. 5 and 6, as given by Hiers.³ It has been realized that the values obtained in a testing machine operated at a normal rate, say a movement corresponding to ¼ in. per min. of free crosshead travel relative to 1 in. of test length of specimen, are markedly higher than those obtained at slow rates in a testing machine or in actual service. At 25°C., the cast alloys are generally stronger than those in the rolled or extruded states. Various studies⁴ of the mechanical properties of the eutectic alloy in fabricated states have been made in England in the last few years.

Hardness—Brinell hardness values for chill castings, as determined by Goebel¹ are shown in Fig. 7. He used a 4 mm. ball with load of 20 kg. applied for 20 sec.

Creep Data—For a 2% tin alloy in the extruded form, Moore⁵ gives 650 psi. as the stress for fracture under steady tensile load for one year. For the same metal, he estimated 4% creep (or elongation) in 10 years at:

275 psi. tensile load at 0°C.
170 psi. tensile load at 25°C.
105 psi. tensile load at 65.5°C.

Tests have been made of the strengths under continuous load of soldered lap seams used for copper roofing in an investigation conducted at the Bureau of Standards.⁶ As a result of these tests, it was decided that the seams should be at least ¼ in. wide, and the maximum safe load for these seams was placed at approximately 350 psi. (length times width) of seam. For ½ in. pretinned flat lock seams 375 psi. of seam area was the maximum safe load. The values apply to the use of a 50% tin solder.

Fatigue Resistance—Moore⁵ has determined 800 psi. as an endurance limit for 2% tin extruded alloy when tested for 50,000,000 cycles of stress at 2,500 r.p.m.

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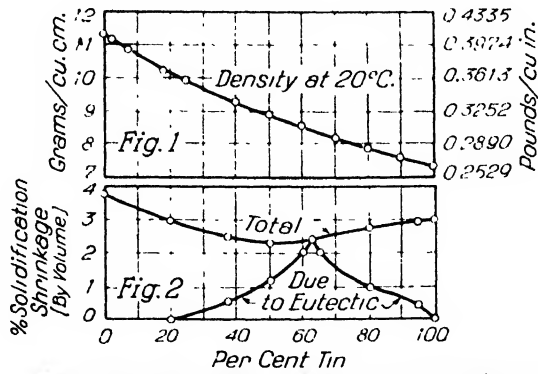


Fig. 1—Density at 20°C. (weight in lb. per cu.in.) vs. composition.

Fig. 2—Volume shrinkage upon solidification.

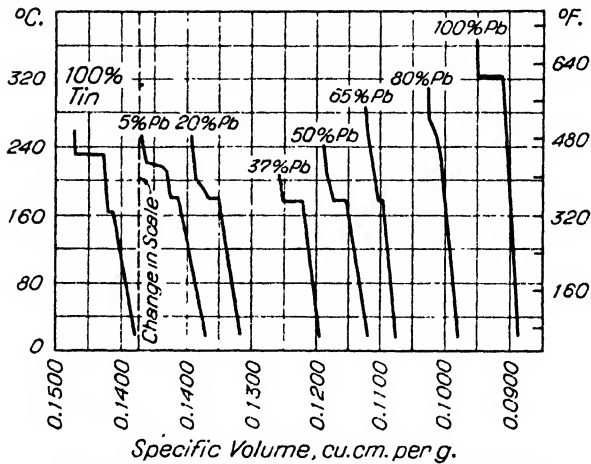


Fig. 3—Typical alloy specific volume vs. temperature.

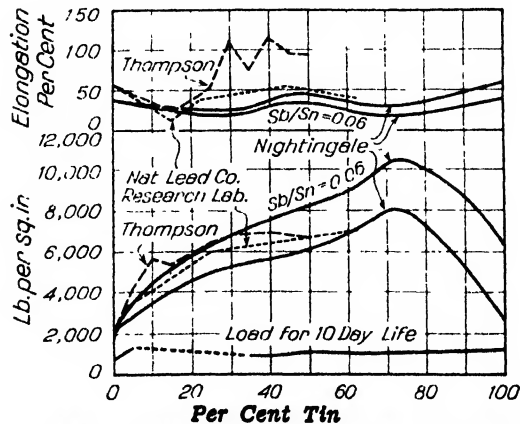


Fig. 4—Tensile strength and elongation at 25°C. Also strength for 10 day life.

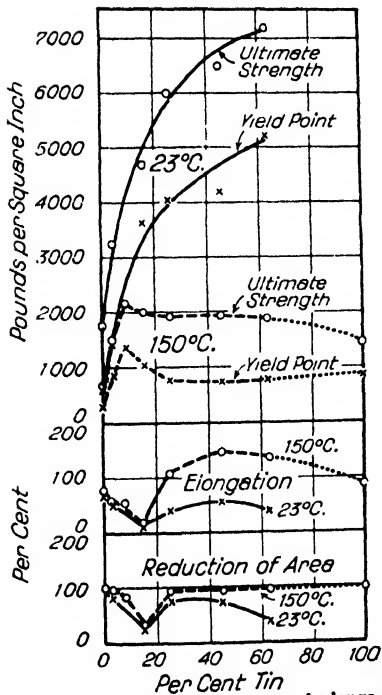
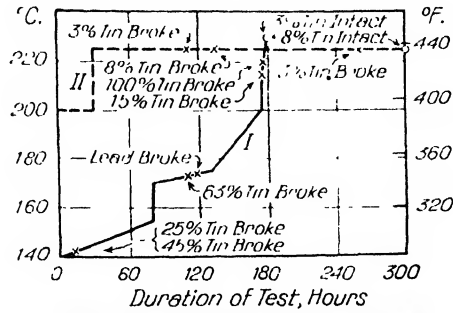


Fig. 5—Tensile strength and elongation at 25 and 150°C.

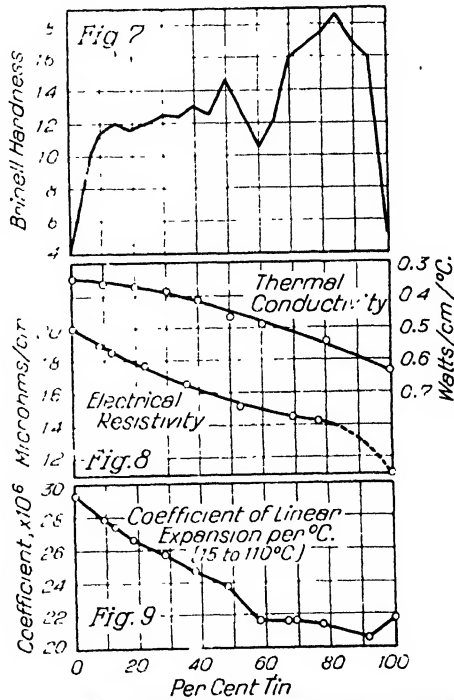


Fig. 7—Brinell hardness for chill castings at 20°C.

Fig. 8—Electrical resistivity and thermal conductivity.

Fig. 9—Coefficient of linear expansion.

Under the same test conditions, he has found commercial lead to have an endurance limit of 400 psi.

Thermal and Electrical Data—Graphs representing data given in the International Critical Tables^{7, 8} are shown in Fig. 8 for Thermal and Electrical Conductivities. Linear expansion⁹ data are given in Fig. 9.

Notes Regarding Solder—While the solder alloys are discussed more fully on page 1205 it may be repeated here that when soldered joints are depended upon for considerable strength, it is well, when possible, to use re-enforcements, such as crimped, lapped, or interlocking seams, rivets, cleats, or bolts, before soldering. Thus the solder may be relieved of the load and its major function becomes that of hermetically sealing the joints.

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The Properties of Lead-Tin-Antimony Alloys

By George O. Hiers*

Constitution—These alloys are important, particularly in use as bearing metals, casting metals, and type metals. There is a ternary eutectic at 462°F. (239°C.) with the composition 84% lead, 4% tin, and 12% antimony. At 477°F. (247°C.) there is a pseudo-binary eutectic point with the composition 80% lead, 10% tin and 10% antimony.¹ This appears to be a eutectic between lead and the compound SbSn.

General Casting Properties—The usual type metals and bearing metals do not greatly differ in composition from the eutectic and the pseudo-eutectic alloys mentioned. They were developed in such regions largely because of fusibility and ease in casting. Contrary to statements in the old literature type metals do not expand on solidification, but actually shrink about 2% in volume while solidifying. Alloys containing more than 12% antimony are preferably chill cast in order to prevent segregation. In the higher antimony alloys cubic crystals of antimony or of beta solid solution (SbSn) tend to float upward in the otherwise liquid metal due to the higher melting point and lower density of the cubes.

Type Metals

	Tin, %	Antimony, %	Liquidus, °F.	Brinell Hardness No.
Electrotype	3	3	570	14
Line type {intertype {linotype }	4	11½	475	22
{Ludlow }				
Stereotype	5	14	493	23
Government alloy	6	12	491	23
Monotype	7	16½	527	26
Foundry type	14	24	605	32

Type Metal—Foundry type metal, linotype, intertype, Ludlow, and monotype are cast automatically in machines operated like typewriters. Newspaper stereotype metal is cast in curved plates, reproducing a replica from a paper or composition matrix. Flat stereotype plates are used for books and other commercial work. Electroplated coatings of nickel, copper, or chromium have been used to prolong the life of the printing face of type metal. The metal recently used in the United States Government printing office is a compromise alloy used in all type casting machines and for making stereotypes.

Electrotype alloy is used for backing thin sheet copper replicas (electrotypes) of type or illustrations. It is cast adherently upon the reverse side of the thin electroplates with the aid of solder foil and flux.

Grid Metal—Alloys containing 6-12% antimony balance lead are markedly improved in casting qualities with the addition of ¼-½% tin. It is for this reason the grid metal in automobile storage batteries (of the starting type) has such composition.

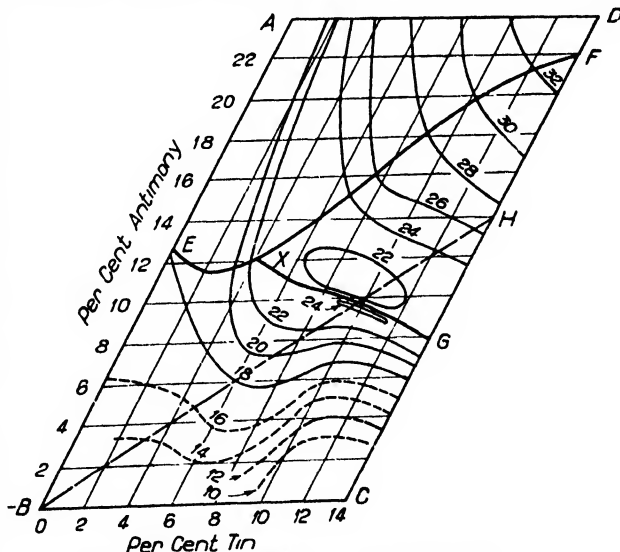


Fig. 1—Iso-hardness diagram Brinell Numbers.

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Table I
Mechanical Properties*

No.	Lead (by dif.), %	Tin, %	Anti- mony, %	Yield Point, Psi.	Tensile Strength, Psi.	Elonga- tion, %	Compression Load required to Compress to Half Length	Brinell Hardness No. 10 mm. Ball 200 kg., 1 min.	Brinell Hardness No. 10 mm. Ball 250 kg., 1 min. Weaver ¹
1	88.0	4.1	7.9	4,800	5,400	1.5	28,448	15.2	18.5
2	88.5	8.6	4.9	4,800	7,220	3.0	N.O.	15.1	
3	81.8	13.1	5.1	6,010	7,500	2.0	N.O.	16.7	
4	76.8	14.8	8.4	6,300	6,900	1.0	N.O.	18.0	
5	72.6	22.1	5.3	N.O.	5,400	—	19,920	16.8	
6	65.7	28.7	5.6	6,610	8,400	1.5	N.O.	15.1	
7	85.2	4.6	10.2	8,990	13,820	10.5	28,200	23.2	21.7
8	82.0	8.9	9.1	8,660	14,400	13.0	24,640	25.4	23.0
9	75.1	14.7	10.2	8,400	14,400	5.5	N.O.	26.4	
10	71.0	18.6	10.4	8,990	11,400	1.5	20,150 C.	23.2	
11	66.8	23.0	10.2	8,400	12,000	1.0	N.O.	24.0	
12	79.6	4.5	15.9	6,900	11,690	4.0	N.O.	25.6	23.0
13	77.1	8.6	14.3	Broken in machining			26,000	31.0	26.0
14	68.4	19.0	14.6	7,800	12,000	—	23,980 S.C.	32.0	
15	66.0	18.9	15.1	7,800	12,000	1.5	21,720 S.C.	27.6	
16	70.1	4.6	25.3	Broken in machining			28,000 S.C.	26.6	
17	68.8	9.1	22.1	10,180	10,180	—	21,950*	37.0	29.5
18	64.1	13.9	22.0	9,000	11,400	—	22,400*	35.6	
19	72.2	4.5	23.3	7,800	7,800	—	19,700*	27.8	
20	65.0	10.0	25.0	Broken in machining			18,590*	33.6	
21	64.2	5.9	29.9	8,400	12,580	1.0	14,500*	28.8	

N.O.—Not observed; C.—Cracks in compression test piece; S.C.—Slight cracks in compression test piece; *—Failed without compression to half length.

Mechanical Properties—Tin strengthens lead appreciably, but antimony does so to a greater extent when added in similar amount. Ellis² studied the tensile strength, compressive strength, and hardness of 21 of the lead-rich ternary alloys containing up to 30% each of tin and antimony. His results are given in Table I. Weaver¹ studied the Brinell hardness of a similar series of alloys with results given in Fig. 1. Test data from the National Bureau of Standards³ are presented in Table III.

Thermal and Physical Properties—Table III gives the density of the alloys and also melting characteristics. Table II shows data pertaining to heat energy required for melting.⁴

Table II
Thermal Data*

	Antimony	Lead	Tin	Babbitt	Babbitt	Type Metal	Type Metal
				80-10-10 Pb-Cu-Sn		86-3-11 Pb-Sn-Sb	82-3-15 Pb-Sn-Sb
Composition							
Mean specific heat, 60° F. to melting point, B.t.u./lb./°F.	0.054	0.032	0.069	0.039	0.038	0.036	0.036
Heat in solid at melting point, B.t.u./lb.	59.7	18.0	26.9	15.8	20.5	15.3	15.5
Latent heat of fusion, B.t.u./lb.	70.0	9.9	24.9	26.2	17.4	21.5	26.2
Total heat in liquid at melting point, B.t.u./lb.	129.7	27.9	51.8	42.0	37.9	36.8	41.7
Mean specific heat of liquid, B.t.u./lb./°F.	0.054	0.032	0.060	0.038	0.037	0.036	0.036
Average pouring temperature, °F.	1,320	720	650	625	820	620	620
Total heat in liquid at pouring temperature, B.t.u./lb.	138.0	31.1	63.8	48.2	46.0	41.6	46.4
Coefficient of linear expansion per °F. (range 63-489°F.)						0.0000108	
(*Mostly based on data taken from Industrial Gas Series, "Combustion" (4).)							

Age Hardening—Solid solubilities of tin and antimony have been determined for the lead-rich corner of the ternary system.⁴ According to Weaver, 2½% each of antimony and tin are soluble together in lead at the eutectic temperature, 477°F. While the rolled and extruded alloys are markedly susceptible to heat treatment and age hardening, particularly in the alloys containing a few percent each of tin and antimony, it so happens that the ternary alloys are used almost exclusively in the cast state. Generally, in the cast state the age hardening of the commercial alloys appears of no consequence. However, storage battery grid metal usually becomes slightly harder and slightly brittle on aging. This appears due to

Table III
Composition and Physical Properties of White Metal Bearing Alloys^a

Compositions of Alloys Tested, %			Specific Gravity	Yield Point, ^b Psi.		Johnson's Apparent Elastic Limit, ^c Psi		Strength, ^d Psi		Brinell Hardness ^e		Melting Point (Solidus) °C.	Temperature of Complete Liquefaction (Liquidus) °C.	Proper Pouring Temperature °C.
Copper	Tin	Antimony	Lead	20° C.	100° C.	20° C.	100° C.	20° C.	100° C.	20° C.	100° C.			
4.56	90.9	4.52	none	4,400	2,650	2,450	1,050	12,850	6,950	17.0	8.0	223	354	441
3.1	89.2	7.4	0.03	6,100	3,000	3,350	1,100	14,900	8,700	24.5	12.0	241	354	424
8.3	83.4	8.2	0.03	6,600	3,150	5,350	1,300	17,600	9,900	27.0	14.5	240	422	491
3.0	75.0	11.6	10.2	5,550	2,150	3,200	1,550	16,150	6,900	24.5	12.0	184	306	377
2.0	65.5	14.1	18.2	5,050	2,150	3,750	1,500	15,050	6,750	23.5	10.0	181	296	366
1.5	19.8	14.6	63.7	3,800	2,050	3,550	1,800	14,550	8,050	21.0	10.5	181	277	346
0.11	10.0	14.5	75.0	3,550	1,600	2,500	1,350	15,650	6,150	22.5	10.5	240	268	338
0.14	5.2	14.9	79.4	3,400	1,750	2,650	1,200	15,600	6,150	20.0	9.5	237	272	341
0.06	5.0	19.9	84.6	3,400	1,550	2,400	950	14,700	5,350	19.0	8.5	237	256	327
0.12	2.05	15.7	82.0	3,350	1,850	2,250	1,200	15,450	5,750	17.5	9.0	242	264	332
0.19	0.09	14.8	84.7	3,050	1,400	2,750	1,100	12,800	5,100	15.0	7.0	244	262	332
0.12	0.11	9.9	89.4	2,800	1,250	2,250	950	12,900	5,100	14.5	6.5	245	259	329

^aThe values for yield point were taken from stress-strain curves at a deformation of 0.125 per cent reduction of gage length.

^bJohnson's apparent elastic limit is taken as the unit stress at the point where the slope of the tangent to the curve is $1\frac{1}{2}$ times its slope at the origin.

^cThe ultimate strength values were taken as the unit load necessary to produce a deformation of 25 per cent of the length of the specimen.

^dThese values are the average Brinell number of three impressions on each alloy using a 10-mm. ball and a 500-kg. load applied for 30 seconds.

precipitation of antimony from a supersaturated solid solution. Hayward⁴ has noted age hardening in a cast alloy containing 3% each of tin and antimony.

Modulus of Elasticity—The following values have been given¹ for Youngs modulus of elasticity in tension:

Typical Lead Base Bearing Metal.....	4,200,000
Typical Tin Base Bearing Metal.....	7,400,000

Corrosion Resistance—The lead-rich ternary alloys are resistant to corrosion and suitable for fire extinguisher nozzles in the die cast form. As the quantity of tin increases from 20%, the alloys are increasingly resistant to tarnishing in the atmosphere and may even be used with satisfaction in humid atmospheres.

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Lead-Base Bearing Alloys

By Leland E. Grant*

General—Alloys of lead have been used as bearing metals for a long time with excellent results. In general these alloys are not quite so satisfactory as are the tin-base alloys under severe service conditions, but their low cost and all around good properties make them desirable in numerous applications. They are especially suitable where they are not subjected to extreme high speeds, heavy loads, or severe impact. When the size of the bearing can be increased they can often replace tin-base metals. A large tonnage is consumed annually by the railroads for freight and passenger car bearings. The alloys are also used for electric motors and machinery bearings. Packing for piston rods and pump shafts are another type of bearing in which they are used.

Two basic types of lead-base bearing alloys are in use at the present time. The older type consists of lead hardened with antimony and tin, with additions of copper or arsenic in special cases. The new type is an alloy containing approximately 98% lead, the remainder being calcium and small amounts of other metals. This type has not yet come into extensive use in America but has been used on the German State R. R. for a number of years.

Specifications—A specification for lead-base bearing alloys has been prepared by the A.S.T.M. Table I was selected from the various alloys included in this specification. The S.A.E. has two specifications, Nos. 13 and 14, for lead-base bearing alloys which are the same as A.S.T.M. alloys 9 and 7 respectively. Table II shows the composition of the journal bearing lining alloy in the A.A.R. specification M-501-34.

It will be noted that the above specifications all call for approximately 65% or more lead. Only in a few alloys used for packing does the lead fall below 65%.

Effect of Antimony—The range of antimony content is quite restricted; it seldom exceeds a maximum of 15% and is generally close to 10% when a minimum amount is needed. Antimony combines with tin to form cubes of the solid solution SbSn in some compositions. When these cubes become so numerous that they are nearly continuous throughout the structure the alloy becomes hard and relatively brittle under impact. This condition is avoided if the antimony does not exceed 15%. Small amounts of the cubes are desirable in heavy duty alloys for the hardness and strength they impart. Antimony also forms a pseudo-eutectic with lead and this constituent is the source of a large part of the strength the alloys possess. Antimonial lead was one of the early lead-base bearing alloys used with satisfactory results. These binary alloys are still used to some extent but the great improvement in properties produced by the addition of 2-5% tin more than compensates for the small increase in cost.

Effect of Tin—The permissible range of tin in these alloys is great. In the softer alloys it may be eliminated entirely as explained above, but a much more serviceable alloy is obtained if about 5% tin is present. The maximum for tin is about 20%. Unlike antimony, it does not cause brittleness in relatively large amounts, but beyond 20% tin no marked improvement in properties for good bearing purposes is obtained. Tin enters into solid solution in both lead and antimony and is present in the compound that forms the major portion of the SbSn cubes. It is in these forms that tin participates in the pseudo-eutectics and other constituents which contribute to the hardness and strength.

Effect of Copper—Segregation may become a problem when the tin and antimony are high owing to the tendency of the specifically lighter cubes to float to the top. This can be overcome by the addition of 1-2% copper. The mechanism by which copper prevents segregation has not been fully explained. Sometimes the copper unites with antimony to form long purple needles of the compound Cu_3Sb . These entangle the cubes and prevent them from rising. However, this is not always the case although the evidence does indicate that some reaction takes place in the molten alloy due to the presence of the copper. Frequently a web-like structure is to be seen in the cubic crystals and it is possible this is a result of the addition of copper. Copper should not be used in the alloys of low tin content as it is likely to cause

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frothing when the alloy is poured, unless the pouring temperature is raised considerably. It is for this reason that copper is limited to 0.5% max. in most of the alloys.

Effect of Arsenic—Arsenic also is effective in preventing segregation. It produces a profound change in microstructure, causing a disappearance of the cubes in those alloys where cubes would normally be formed and refining the entire grain structure very markedly. It appears to prevent segregation through a reaction with the normal constituents of the alloys, the effect becoming more pronounced with increasing arsenic. In addition to preventing segregation it raises the hardness at both normal and elevated temperatures. There has been a limited amount of arsenical lead-base bearing alloys marketed in which up to 2.5% arsenic is incorporated. Generally it is substituted for a large part of the tin. Such alloys have not been used extensively probably because they are relatively brittle when the arsenic exceeds 1%. Where brittleness is not serious but where segregation is to be prevented in large bearings such as those for rolling mills, this alloy is used.

Impurities—Little information is available on the effect of impurities on the properties of the lead-base bearing alloys. There is no indication that the small amounts of foreign metals associated with lead and tin are harmful. On the contrary they appear to be beneficial since they act as hardeners in the commercially pure alloys and thus contribute somewhat to the final hardness and strength exhibited by the bearing alloys. Arsenic is normally the principal impurity and its effect has been discussed. Zinc acts in a manner similar to arsenic, increasing the hardness and preventing segregation, but the method by which it prevents segregation is unknown.

Brinell Hardness—The Brinell hardness of the lead-base bearing alloys naturally varies with the composition. Most of the alloys used commercially have a Brinell number between 18 and 23 at 70°F. (10 mm. ball and 500 kg. load). Those that do not contain tin will have a Brinell hardness of around 15. Increase in temperature causes rapid softening so that at 212°F. the hardness is approximately one half of the value at 70°F.

Compression Strength—The ultimate strength in compression of these alloys not containing tin normally lies between 14,000 and 16,000 psi. at 70°F. and decreases more rapidly in proportion than does hardness with increase in temperature. It is apparent from this that overheating of this type of bearing alloy is likely to result in excessive squashing of the lining. The hardness and strength of the lead alloys are significantly lower than the similar values for the tin-base bearing alloys.

Casting Properties—Lead-base alloys have low pouring temperatures (617-653°F.) and excellent casting properties. The metal retains its fluidity down almost to the freezing point (about 465°F. for a majority of the alloys). These properties are a distinct advantage as the casting operations are simplified thereby and at the same time loss of metal by drossing in the melting pot is reduced.

Pouring temperature and rate of cooling exert a profound influence on the microstructure and physical properties of this class of alloys. Too rapid cooling leads to the formation of a structure too fine for the production of the best bearing alloys. Too slow cooling, high pouring temperature, and a mandrel or back that is too hot, promote segregation and formation of a coarse structure with a tendency to brittleness, low compressive strength, and low hardness. The compressive strength and hardness increase with the pouring temperature to maximum values at about the recommended pouring temperatures and then decrease. It is the effect of this variation in cooling rates that undoubtedly accounts for differences in the physical properties that are found in the literature for alloys of essentially the same composition.

Lead-Calcium Bearing Alloys—There are two commercially important bearing alloys containing 97% lead. These are Bahnmetall and Satco. A typical composition of Bahnmetall is as follows:

Lead 98.63, calcium 0.69, sodium 0.62, lithium 0.04, aluminum 0.02%.

The Satco alloy contains tin, magnesium and calcium as the principal hardening elements. Bahnmetall has a Brinell number of 25-35 at 70°F. and Satco about 20. The hardness does not fall off with increase in temperature as rapidly as in other lead-base bearing alloys. These alloys also have higher compressive strengths which fall but slowly when the temperature is raised. Bahnmetall has a compressive strength of 25-30,000 psi.

Bahnmetall has a number of valuable properties but lacks some of the good characteristics of the ordinary lead-base alloys. Its pouring temperature (878-

1112°F.), coefficient of expansion, rate of wear, and shrinkage are all high. The alloy drosses heavily and thereby loses its hardening elements so rapidly that it cannot be remelted and used a second time. Adhesion to solder is poor and mechanical anchorage must be relied upon to hold the lining. Admixture with ordinary lead-tin-antimony alloys causes the hardening elements of Bahnmittel to separate. The metal will carry heavy loads and stand considerable abuse without damage. This is partly due to its relatively high hardness and good plasticity. Temperatures that would cause other lead-base bearings to run out do not harm Bahnmittel. Liners of this alloy can be cast accurately to size and applied without broaching, an item of considerable economic significance in the case of railroad car bearings. But under heavy loads and fairly high speeds the alloy has a tendency to develop hair line cracks which ultimately cause failure.

Satco does not lose its hardening constituents readily when melted but it does form a large volume of dross compared with lead-base babbitts. This is due in part to the high pouring temperature required (932-1004°F.). The alloy solders readily with any of the common solders and makes a strong bond. It can be handled in the same equipment as is used for ordinary babbitts but due allowance must be made for the high pouring temperature. It should not be contaminated with ordinary lead-base bearing metals. It stands pounding well, has about the same wear rate as other lead-base babbitts, and is not damaged by local overheating that would be likely to ruin an ordinary lead-base alloy. Satco is being used to some extent in automotive, railroad, marine, and general industrial service, but its ultimate sphere in the bearing field cannot yet be determined.

Table I
Properties of Lead-Base Bearing Alloys¹

No.	Sn	Sb	Pb	Cu	As	Ultimate Strength*, psi.		Brinell Hardness		Pouring Temp. °F.
						68°F.	212°F.	68°F.	212°F.	
6	20	15	63½	1½	0.15	14,550	8,050	21.0	10.5	655
7	10	15	75	0.50 max.	0.20	15,650	6,150	22.5	10.5	640
8	5	15	80	0.50 max.	0.20	15,600	6,150	20.0	9.5	645
9	5	10	85	0.50 max.	0.20	14,700	5,850	19.0	8.5	620
10	2	15	83	0.50 max.	0.20	15,450	5,750	17.5	9.0	630
11	..	15	85	0.50 max.	0.20	12,800	5,100	15.0	7.0	630
12	..	10	90	0.50 max.	0.20	12,900	5,100	14.5	6.5	625

*The ultimate strength values were taken as the unit load necessary to produce a deformation of 25% of the length of the specimen.

¹From A.S.T.M. Standards, Designation B23-26, Part I, p. 841, 1933.

Percentage of Element Specified	Permissible Variations Over or Under the Specified Value, %
Not over 2%	0.25
Over 2 to 5%, incl.	0.50
Over 5 to 10%, incl.	0.75
Over 10%	1.00

Table II
A.A.R. Specification for Journal Bearing Linings

	Specification %	Average Composition %
Tin.....	As specified	4.0
Antimony, min.	8.0	9.0
Tin and antimony.....	10 to 14	13.0
Arsenic, max.	0.20	0.14
Copper, max.	0.50	...
Sum of tin, lead, antimony, and arsenic (min.).....	99.25	...

Preparation of Lead and Lead Alloys for Metallographic Examination

By J. R. Vilella*

Polishing—Because of the softness of lead and its alloys, the preparation of specimens for microscopic examination has always been a difficult task. Two main difficulties are encountered:

1. The finished surface is usually too heavily scratched.
2. The surface metal flows, forming a layer of cold worked metal that masks the true structure.

The usual way of overcoming these difficulties has been to etch deeply so as to get below the surface imperfections. However, a deep chemical attack roughens, blackens and obliterates the fine details of the structure. It is therefore desirable to be able to finish the samples with a minimum of scratches and flowed metal so as to permit light etching.

Two basic methods and several modifications thereof intended to overcome these difficulties have been described.^{1,2} One of these is based on the use of a robust rigid microtome, equipped with a specially sharpened knife capable of producing a smoothly cut surface suitable for etching and microscopic examination without further polishing. The other method requires no special equipment. It is based on the fact that scratches and flowed metal can be eliminated by a series of alternate light polishings and etchings.

Microtome Method—The success of this method depends on three factors:

1. The microtome must be sufficiently rigid for the service.
2. The knife must be properly sharpened.
3. The instrument must be capable of cutting slices 2 microns in thickness.

1. Lucas, who originated the method, employs a Jung microtome, type K, originally designed for wood sectioning, but he states that given a solid, substantial instrument, good results are largely a matter of personal skill in sharpening the knife and manipulating the apparatus. Schumacher and Bounton³ have successfully employed an inexpensive biological microtome. They have also obtained fair results by means of a wood chisel and a special clamp.

With the Jung microtome specimens of lead, tin, platinum, gold, and silver have been successfully sectioned. Harder metals such as aluminum, aluminum alloys, copper, zinc, and the brasses and bronzes may be roughly prepared by sectioning, and then given a final polish on magnesium oxide, thus considerably expediting the usual procedure of preparation.

2. A properly sharpened, honed and stropped knife is indispensable for the success of this method. A dull or serrated edge will yield surfaces covered with scratches and cold worked metal. An edge such as is usually associated with razors is also unsatisfactory because it chips and turns over easily. Best results are obtained when the knife is sharpened to a fine chisel edge and free from all but the finest imperfections. Once a good edge is obtained, if used judiciously, it will cut 50 or more lead specimens between stroppings. Sharpening the knife is a laborious operation requiring considerable skill. Detailed instructions are usually supplied by the manufacturers.

3. Lucas finds that unless the instrument cuts sections as thin as 2 microns the cut surface is not suitable for etching. The shavings themselves are not used for metallographic study, but if they are thicker than 2 microns it will be found that the cut surface of the specimen will contain cold worked metal and scratches. This is an indication that the knife has not been properly honed or stropped. It should be noted that even well cut and etched specimens present to the unaided eye the appearance of slight furrows or undulations on the prepared surface. These imperfections are not troublesome under the microscope.

Wood Chisel Method—This method gives satisfactory results when properly used. The specimen is mounted in a hardened tool steel clamp and the excess material

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¹For the references, see the article "Etching Lead and Lead Alloys for Metallographic Examination," which follows this article.

²This article not revised for this edition.

removed with a coarse hacksaw. A rough chisel cut is made, followed by a fine one using the surface of the clamp as a guide.

Polishing with Standard Equipment—This method is rapid and can be successfully carried out with ordinary polishing equipment, or by hand, and when properly executed leads to the formation of ideal surfaces for microscopic examination at both low and high magnifications.

Procedure—(1) To minimize distortion of the surface metal, the sample should be cut with a sharp hacksaw, taking care to avoid dragging and pushing. It is well to smear the saw blade with a few drops of oil.

(2) The specimen should then be ground with gentle pressure on a coarse emery paper that has been previously smeared with a concentrated solution of paraffin in kerosene. This prevents the particles of lead from adhering to the paper and forming a glaze which drags and distorts the surface metal. At least $\frac{1}{4}$ inch of metal should be ground away during this step. The speed of the revolving disks should not exceed 500 r.p.m. at any stage during the entire operation.

(3) The specimen is then ground successively on No. 2, No. 1, No. 0, No. 00, and No. 000 emery papers, all previously smeared with the solution of paraffin in kerosene. Grinding on successive papers should be continued for at least one minute after all the scratches left by the preceding one have disappeared, and care should be taken to exert the minimum pressure needed to secure good cutting action. The scratches left by No. 000 paper are frequently too deep to be easily removed during the next step (wet polishing), and for this reason the specimen should be ground, when necessary, on an old No. 000 paper that has been well worn by previous use. This last paper as a rule yields very fine, even scratches, which disappear easily during wet polishing. The specimen should now be free of all paraffin and grit.

(4) Wet polishing is carried out on a perfectly clean broadcloth smeared with an abundant supply of soap. The abrasive to be used is a water suspension of the finest levigated alumina obtainable. At this stage of the operation a black smudge often appears on the surface of the specimen. When this happens, polishing should proceed very gently, taking care to keep the cloth thoroughly wet with alumina and soap until all traces of smudge have disappeared and the surface appears bright.

(5) The scratches left after polishing on broadcloth are often rather deep and remain visible after etching. They can be removed by finishing the operation by hand on a clean pad of silk velvet well soaked with soap and alumina. The sample is then washed carefully to remove all traces of soap.

Etching Lead and Lead Alloys for Metallographic Examination

By J. R. Vilella*

According to the proponents of the sectioning methods of preparing lead specimens, it is feasible to etch the sample as it comes from the microtome. One etching is sufficient to disclose the true structure of the metal. Occasionally a preliminary swabbing with cotton well soaked in the etching reagent is employed to eliminate the heavier knife marks usually present in specimens prepared by the microtome or chisel methods.

The etching of specimens prepared by conventional polishing methods is not considered a process completely independent of polishing. Even well prepared surfaces are seldom completely free from a film of cold worked metal which must be eliminated in order to show the true structure of the specimen. This is not always satisfactorily accomplished by the etching reagent alone, no matter how long the specimen is exposed to its action. A prolonged etching attack usually results in pitting, roughening and obliterating the fine details of the structure. It is advantageous to employ a method of alternate polishing and etching by means of which the film of distorted metal is gradually removed by the reagent, while the succeeding light polishings prevent the evils of a long continued chemical attack. This process may be carried out as follows:

The polished specimen is etched in a suitable reagent and its structure noted under the microscope. It is then repolished gently on the velvet pad until bright, and reetched and examined again. A considerable improvement in the appearance of the structure will be noted. It should be again repolished and reetched, and this process continued as long as the appearance of the structure improves. As a rule, three repolishings suffice, but occasionally more may be required.

The etching reagents for lead and lead alloys are given in Table I.

Table I
Etching Reagents for Lead and Lead Alloys

No.	Authority	Composition	Remarks
1	Rutherford ⁴	3 parts glacial acetic acid 1 part 9% hydrogen peroxide	Etch for 10-30 min., depending on depth of flowed metal on the surface. Dry with alcohol and clean with concentrated nitric acid. The nitric acid is removed by sudden immersion in a large volume of water.
1a	Lucas ^{1,2}	3 parts glacial acetic acid 1 part 30% hydrogen peroxide	Etching time varies from 6-15 min. Used for lead, lead-tin, lead-antimony, and lead-calcium alloys.
2	Vilella ³	1 part glacial acetic acid 1 part nitric acid 4 parts glycerol	Etching from 10-15 sec. Best results obtained when used in conjunction with method of alternate polishing and etching. For lead, lead-antimony, lead-calcium, and low tin alloys. Use freshly prepared solution and discard after using.
2a	Bassett and Snyder ⁵	3 parts glacial acetic acid 4 parts nitric acid 16 parts water	Used at a temperature of 40-43°C. Recommended for pure lead and lead-tin alloys up to 3% tin. Etching time depends on depth of distorted metal on prepared surface.
3	Johnston ⁶	Concentrated nitric acid	Plunge specimen in concentrated acid. Wash in a rapid stream of water. Repeat operation as often as necessary. If acid becomes diluted by water carried by specimen it must be rejected and fresh acid used.
4	Bassett and Snyder ⁵	60% solution of perchloric acid	For electrolytic etching. No. 6 dry cell used to supply energy. Also recommended by Dean, Ziekrick and Nix. ⁷

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Properties of Lithium and Its Alloys

By Dr. Hans Osborg*

Introduction—Lithium resembles sodium, potassium, caesium, magnesium, calcium, strontium, and barium. However, the diversity in reactivity of lithium is greater than these other elements. Furthermore, the solid solubility of lithium in certain metals is somewhat greater than that of other alkali and alkali earth metals. These two characteristics make lithium useful as a refining agent and as an alloying constituent.

Lithium as a Refining Agent—Lithium melts at 366.8°F., its boiling point is approximately 2435°F. The vapor pressure of molten lithium is relatively low. At 1700°F., it is only 17 mm. Hg, and at 1775°F. it is not more than approximately 95 mm. Hg.

Lithium combines with oxygen, sulphur, hydrogen, nitrogen, carbon oxides, and silicates. It forms rather stable compounds which are of a nonmetallic nature and possess relatively low melting points, or are volatile at pouring temperatures, and which possess also a low specific gravity. While the intensity with which lithium reacts is considerably less than that of the alkali metals, the heat of formation of lithium compounds is high and ranks among the highest for the respective compounds. This apparent anomaly is explained by the fact that the lithium atom and ion are of small size and that in accordance with the law of Coulomb the energy, or heat of formation, discharged is the greater the closer the reacting, or combining particles can approach each other. Table I compares the amount of oxygen and sulphur with which lithium and some other elements combine. It also gives the number of kilogram-calories which are set free by the respective reactions. While the table is self-explanatory, it may be added that lithium does not form refractory compounds as practically all other elements do which have also a relatively high affinity for oxygen.

Table I
Reaction of Oxygen and Sulphur with Various Elements*

Element	G. of oxygen which combine with 1 g. of ele- ment	Kg.-cal. set free when 1 g. of ele- ment combines with oxygen	G. of sulphur which combine with 1 g. of ele- ment	Kg.-cal. set free when 1 g. of ele- ment combines with sulphur
Li	1.152	10.33	2.309	8.75
Na	0.348	2.18	0.697	1.95
K	0.204	1.11	0.410	1.11
Rb	0.094	0.46	0.188	1.02
Cs	0.060	0.31	0.120	....
Be	1.774	15.23	3.554	....
Mg	0.658	6.00	1.320	3.27
Ca	0.399	3.72	0.800	2.78
Sr	0.182	1.61	0.366	1.258
Ba	0.116	0.97	0.234	0.745
Al	0.890	7.05	1.783	2.34
Zn	0.245	1.27	0.491	0.632
Mn	0.292	1.707	0.583	1.10 (approx.)
Si	1.140	6.80	....	....
Ti	0.668	4.56	....	....
P	1.289	5.78	....	....
Zr	0.350	2.90	0.351	....

Refining, Degasifying, and Deoxidizing—The high affinity of lithium for practically all elements which occur as nonmetallic impurities and gases in metals and alloys permits the use of lithium as a highly efficient scavenging agent. Lithium may be applied either as lithium metal or diluted with the metal to be treated, or alloyed with an alkali earth metal. These lithium-alkali earth alloys, of which the 50/50 and 30/70% lithium-calcium alloys have been produced in commercial quantities, are in many instances more effective than lithium or the alkali earth metal alone. Furthermore, the lithium-calcium alloys are of high purity, can be handled with great convenience, and cost less than lithium.

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The treatment of molten metals and alloys with lithium and lithium-calcium alloys is carried out in the furnace or in the ladle. In applying the treatment, it should be borne in mind that the specific gravity of lithium is as low as 0.5, so care should be taken to prevent the lithium or lithium-calcium alloy from rising to the surface of the molten mass. In the case of chromium alloys, the ladle should be covered as the reaction is rather violent. In practically all other instances, the treatment properly applied is carried out with convenience and in a simple manner similar to the application of the conventional phosphorizer in treating copper and copper alloys.

Table II
Intermetallic Compounds of Lithium^a

Element	Formula	Stable Up to °C.	Melting Point, °C.
Mg	Li ₂ Mg ₃ ?	...	592
	LiMg ₂	...	600
Al	Li ₃ Al	521	...
	LiAl	...	698
	Li ₂ Al ₃ ?	...	598
Zn	LiZn	...	...
	Li ₂ Zn ₃	...	520
	LiZn ₃	93	...
Cd	Li ₂ Cd	272	...
	LiCd	...	549
	LiCd ₃	370	...
Hg	Li ₂ Hg	379	...
	LiHg	...	600.5
	LiHg ₂	232	...
	LiHg ₃	- 42	...
Tl	Li ₄ Tl	381	...
	Li ₂ Tl	...	447
	Li ₃ Tl ₃	...	448
	Li ₂ Tl	381	...
	LiTl	...	508
Pb	Li ₄ Pb	648	...
	Li ₇ Pb ₃	...	726
	Li ₃ Pb	658	...
	Li ₅ Pb ₂	642	...
	LiPb	...	482
Bi	Li ₃ Bi	...	1,145
	LiBi	415	...
Ag	Li ₃ Ag	...	450
	LiAg	...	955
Sn	Li ₄ Sn	...	765
	Li ₇ Sn ₃	...	783
	Li ₅ Sn ₃	720	...
	Li ₃ Sn	502	...
	LiSn	...	485
	LiSn ₂	326	...

Due to the low equivalent weight of lithium (6.94), the amount of lithium or lithium-calcium alloys sufficient for the treatment is often as low as 0.005% lithium. Of course, the percentage required for the treatment will depend on the degree of purity of the metal or alloy to be treated.

Lithium as an Alloying Element—Lithium alloys readily with a number of light and heavy metals, including silicon. No alloys of lithium are known with metals of the iron and platinum groups. In the case of copper, it is doubtful whether true alloys are formed if more than 0.1% lithium is present in the copper. Silver, however, alloys with lithium and two intermetallic compounds of silver with lithium have been determined.

In a number of metals, the solid solubility of lithium is greater than that of other alkali and alkali earth metals. Typical examples are aluminum and lead. If the addition of lithium is kept within the solid solubility range, it strengthens and toughens the matrix, producing improved strength, improved elastic properties, and greater hardness. Should the percentage of lithium added exceed the solid

solubility, precipitation and age hardening occur and the physical properties of the base metal or alloy are further improved. The effects produced are similar to those observed on alloys containing magnesium and magnesium silicide. The best known examples for this type of lithium alloys are zinc die casting alloys containing less than 0.1% Li. Still higher additions of lithium, from 1-2% upward, embrittle the alloy due to the formation of intermetallic compounds of lithium with other constituents of the alloy.

The intermetallic compounds of lithium are numerous and interesting in several respects. Table II lists the intermetallic compounds which have been investigated up to 1937. From Table II, it becomes apparent that many of these intermetallic compounds are rather stable and have well defined melting points which range from approximately 450 to approximately 1150°C. Of special interest are the compounds LiHg, with a melting point of 600.5°C., and Li₃Bi, with a melting point of 1145°C. The intermetallic compounds of lithium have been of great service in investigations concerned with the nature and characteristics (atomic arrangements and physico-chemical properties) of intermetallic compounds in general. Nothing is known yet regarding the constitutional diagrams of other metals with stable intermetallic compounds of lithium.

Lithium Metal—The metal is silvery white, softer than lead, and tarnishes quickly upon exposure to the atmosphere. It must be kept in air tight containers or under kerosene. If exposed to moist atmosphere, Li₃N is slowly formed. Nitrogen penetrates solid lithium metal, forming the nitride. Lithium metal is produced in commercial quantities by means of electrolysis of fused LiCl in a mixture of chlorides. Specific gravity: 0.534; melting point: 186°C; purity: 99.5%+.

Lithium-Calcium Alloys—This alloy is silvery white, metallic luster, hard and brittle from about 50% lithium downward. The 25% Li-75% Ca alloy is as brittle as glass and can be finely ground (under oil). It must be kept in air tight containers or under kerosene. Lithium-calcium alloys react more slowly with the atmosphere than lithium. The 50-30% lithium, balance calcium, alloys have a melting range of about 230-260°C. The specific weight of these alloys is approximately 0.8-1.2, depending on the lithium content. The 50/50 and 30/70% alloys have been produced in commercial quantities by electrolysis of the fused chlorides.

Lithium-Copper—Lithium-Copper is a high conductivity, high density alloy possessing deep drawing properties and containing residual lithium and calcium in minute amounts. It is produced^a by treating molten electrolytic, or other copper of equivalent purity with a 50% lithium-50% calcium alloy in small, controlled amounts. The process is carried out in conventional melting and casting equipment. The casting can take place in the presence of air as some of the residual lithium alloy vaporizes and envelopes the stream of molten copper, thus preventing re-oxidation. The process is flexible and permits of producing oxygen-free copper, as well as so-called low oxygen copper by leaving residual oxygen in the copper in controlled and predetermined, minute amounts. About 180 grams of the lithium alloy per ton of copper sufficiently deoxidize copper which has been poled to approximately 0.025% oxygen. In case of overpoled copper, the treatment produces likewise satisfactory results since the lithium-calcium alloy readily reacts with hydrogen forming rather stable salt-like hydrides which are insoluble in copper.

Lithium-Copper has the following properties:

Conductivity, I.A.C.S. ^a	101.5% ± 0.5
Number of bends after annealing in air ^b	18-24
Number of bends after annealing in hydrogen ^b	16-24
Density, as cast ^c	8.92
Izod impact (air) ^d	10-13 (10.5 av.)
Izod impact (hydrogen) ^d	10-13 (10.9 av.)
Tensile strength, ^a psi	31,500 to 36,500
Elongation, % in 2 in. ^a	72-60
Residual lithium, %, approx. ^e	0.005-0.008
Residual calcium, %, approx. ^e	0.005-0.01

^aElectrical conductivity, tensile strength and elongation determinations made on wire having a diameter of 0.325 in., annealed in salt-peter at 1050°F.

^b0.08 in. wire annealed 30 min. at 1550°F. in air, or in hydrogen, respectively.

^c3 in. billets, top (shrinkage) cropped off, used for density determinations by immersion method. One-third of the billets had a density of 8.96, the other two-thirds as shown above.

^dIzod impact V-notch 0.080 in. deep, 0.325 in. wire. Energy of blow: 20 ft. lb. Specimens annealed 30 min. at 1550°F. in air, or in hydrogen, respectively.

^eDetermined by gravimetric method against standard samples of known compositions containing Li and Ca percentages of same magnitude.

Lithium and Lead—The solid solubility of lithium in lead is more than 0.06 and less than 0.09%, by weight (about 6-8 times greater than calcium). (At room temperatures, 70 atoms of lithium are soluble in the same number of lead atoms as 1 atom of calcium). This high solid solubility of lithium is used to advantage in lead-base bearing alloys and in workable and extrudable lead and lead alloys. The addition of lithium hardens lead-base bearing alloys. These alloys possess a relatively high hardness at elevated temperatures, high resistance toward deformation, and satisfactory wearing qualities as journal bearings, and the like.⁴ The percentage of lithium in lead-base bearing alloys is approximately 0.04%.

Workable and extrudable lead and lead alloys containing lithium have about twice the strength of lead. The increased strength and higher hardness do not appreciably reduce the ductility. The percentage of lithium in high strength lead alloys ranges from about 0.01-0.03%. Up to a lithium content of approximately 0.025%, the corrosion resistance is quite satisfactory.

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Magnesium Industry

By W. G. Harvey*

Magnesium was isolated as a metallic element and some of its properties determined as early as 1830. Commercial production however was not attempted until the beginning of the twentieth century. Its outstanding characteristic is its lightness with its specific gravity of approximately 1.74 or approximately two-thirds that of aluminum. It is the lightest commercial metal and the increase in production which has occurred in recent years can be attributed to this characteristic and the demand for weight saving where lightness in portable and moving equipment is essential.

Occurrence—Magnesium does not occur in nature as a metal but in combination with other elements it constitutes approximately 2% of the earth's crust. The minerals are numerous and widely distributed. As a source of metallic magnesium, the only ones of importance are magnesite, dolomite, carnellite, and certain natural salt brines containing magnesium chloride. The latter occur in several locations in the United States. They are at present the chief source of the metal produced in this country. From them a pure magnesium chloride can be obtained which is responsible for the high commercial purity of the present day production.

Extraction Methods—Electrolytic methods are the electrolysis of magnesium oxide in a mixture of molten fluorides and the electrolysis of molten magnesium chloride either alone or mixed with other fused chlorides to lower the melting point and obtain a lower operating temperature. Magnesium chloride as a base material may be obtained by either chlorinating magnesite or dolomite or by separating it from the natural sodium chloride brines in which it at times occurs. The latter method produces a metal with a purity in excess of 99.8%. The production in the United States in 1937 was in excess of 4,000,000 pounds.

Principal Products—Pure magnesium is available in the form of metallic ingots of several sizes; in the form of powder, wire, ribbon, and extruded strip. The magnesium alloys are available in the form of sand, permanent mold, and pressure die castings; as extruded round, square, hexagonal, and rectangular rod, and special shapes; in the form of rolled plate and sheet; and as hot pressed forgings.

Alloys—The mechanical strength of pure magnesium is not high and it is therefore unsuitable for applications where more than moderate stresses are involved. Satisfactory mechanical properties are obtained by alloying the pure metal with small amounts of other metals. With the exception of iron, chromium and to a limited extent, manganese, magnesium alloys with most of the common metals. The majority of these do not form attractive combinations and the ones which do produce satisfactory strength and forming properties are those containing aluminum or zinc or both. These alloying ingredients amount in general to less than 10% so that the magnesium alloys of commerce contain in excess of 90% magnesium. Table I gives the composition of the principal magnesium alloys used for various products.

Table I
Typical Composition of Magnesium Alloys

Aluminum, %	Zinc, %	Manganese, %	Magnesium	Characteristic Use
6.0	3.0	0.3	Balance	Sand, permanent mold, and pressure die castings
10.0	none	0.2	Balance	Sand, permanent mold, and pressure die castings
8.5	0.5	0.2	Balance	Extruded rod, shapes, and press forgings
6.5	0.75	0.3	Balance	Extruded rod, shapes, and press forgings
4.0	none	0.3	Balance	Rolled sheet and plate
none	none	1.5	Balance	Rolled sheet and plate

Fabricating Methods—Magnesium alloys react with moisture at or above their melting points and sand castings, for instance, cannot be successfully made in the green sand molds employed by most foundries. It has been found necessary to incorporate inhibitors in the sand to prevent this reaction and a number of these are effective. Among the best are sulphur, boric acid, ethyl glycol, ammonium fluoride salt or combinations of these substances. A small amount of the inhibitor thoroughly mixed with the green sand is sufficient. Some modification of standard

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casting methods must also be employed to compensate for the lighter weight of the molten metal. This is accomplished by employing more gates and risers and making all of these of greater cross section.

Most of the magnesium alloys employed for casting are capable of heat treatment with improvement in mechanical properties and this procedure is followed when the castings are to be used for highly stressed applications.

The magnesium alloys can be extruded into practically any shape for which die equipment can be constructed. The alloys are plastic within the range of 500-650°F. and at this temperature can be pressed into dies producing hot pressed forgings.

Sheet rolling methods employ an initial breakdown of either large cast ingots or extruded slabs at an elevated temperature. This operation reduces the slabs to approximately $\frac{1}{4}$ in. thickness. Rolling is continued by the hot slabbing until the thickness reaches $\frac{1}{8}$ - $\frac{1}{16}$ in. Further reduction is accomplished by cold rolling. This cold rolling produces satisfactory mechanical properties and surface finish. It is necessary to anneal the sheet frequently during the cold rolling. Present practice will produce sheet approximately 60 in. wide by 144 in. long down to 9 B. & S. gage; 30 in. wide by 144 in. long down to 20 gage; and 20 in. wide by 72 in. long in 30 gage.

Uses—There are a number of uses for pure magnesium based on its chemical properties. In the form of ingot it is an excellent deoxidizer for such metals as brass, bronze, and nickel silver. Due to its affinity for oxygen and nitrogen it removes these substances from nonferrous melts with the formation of light magnesium oxide which, rising to the surface, can be skimmed off. It is particularly useful in the nickel industry through its ability to reduce nickel sulphide and render the nickel malleable. The quantity of magnesium required for this purpose is small and varies from 0.05-0.2%.

Magnesium is also an important constituent in the alloys of other metals. A number of the high strength aluminum alloys contain from 0.2% to as high as 10.0% magnesium. In the form of powder, magnesium is used in many types of pyrotechnics for photography; for marine and railroad signals, and for military applications. Shavings and coarse powder are used for the synthesis of certain organic chemicals by the Grignard reaction. Rolled sheet is used in certain forms of dry rectifiers for changing alternating to direct current.

While these uses for the pure metal were responsible for the starting of the magnesium industry they were not sufficient to warrant the present day production. It is the combination of high strength and lightness, combined with good machinability which can be obtained in castings; in extruded rod and shapes which account for the increasing growth of this industry.

In the form of sand and die castings; as extruded rod and rolled sheet the magnesium alloys are used in many industrial applications. Practically all of these uses take advantage of the combination of light weight with strength and excellent machinability. The magnesium alloys have approximately two-thirds the weight of aluminum and one-fourth the weight of brass. Commercial uses for the products are extensive and the following are given as typical examples. In aircraft, castings are used for engine crankcases, accessory drive housings, oil pumps, intake manifolds, for landing wheels, engine starters and for many parts of the airplane. In high speed equipment they are used for reducing the weight of the moving parts of bread slicers, textile equipment parts, packaging equipment, envelope folding machines, cigarette machines, and other pieces of equipment of this general nature. Magnesium alloy products are also useful in reducing the weight of portable equipment, such as foundry flasks, patterns and match plates; for drilling equipment and for many types of portable tools.

Statistics—The consumption of magnesium alloy products for the years 1934, 1935, and 1936 are given in Table II which has been compiled from statistics published by the United States Department of the Interior.

Table II
Magnesium Products in Pounds Produced in the United States

	1934	1935	1936
Ingot	4,249,838	4,241,318	3,903,312
Alloy	237,693	307,470	872,020
Fabricated Products.....	634,183	673,956	1,042,026

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Constitution of Magnesium-Aluminum Alloys

By H. E. Bakken* and R. T. Wood†

The magnesium-aluminum system was first studied by Boudouard.¹ The earliest accepted constitution diagram was determined by Grube.² The comprehensive work of Hanson and Gayler³ greatly advanced the understanding of the magnesium-aluminum system. Since the publication of the Hanson and Gayler diagram, other investigators have suggested modifications, notably to that part of the diagram pertaining to the solid solubility of aluminum in magnesium. Except, however, for relatively minor changes in the shape and position of the line of solid solubility of aluminum in magnesium, the diagram of Hanson and Gayler is at present considered authoritative by most metallurgists.

The magnesium-aluminum system cannot be considered a simple one, as it contains two compounds and three eutectics. Each metal is appreciably soluble in the other in the solid state and the compounds also form solid solutions. The diagram

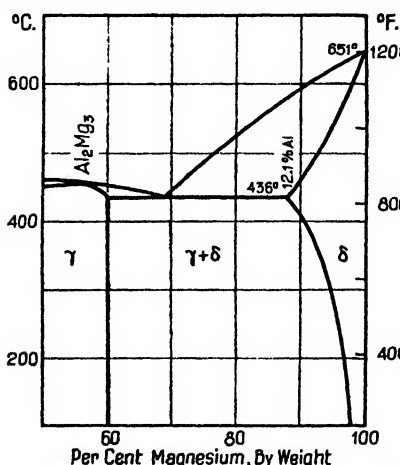


Fig. 1—Magnesium-aluminum constitution diagram (Hanson and Gayler). Solid solubility line according to Schmidt and Spitaler.

shown in Fig. 1 is essentially that of Hanson and Gayler³ with the exception that the line of solid solubility of aluminum in magnesium has been changed to conform to the data of Schmidt, Seliger and Siebel. In the modified form the solid solubility of aluminum in magnesium is placed at 12.1% at the eutectic temperature (436°C.) and 2.6% at 150°C.

The scope of this discussion is limited to the magnesium rich portion of the system. Referring to Fig. 1 it will be seen that the liquidus falls from 651-436°C., the freezing point of the eutectic, as the aluminum content increases from 0-32%. The liquidus is nearly a straight line. At the eutectic composition, 32% aluminum and 68% magnesium, the liquidus and solidus coincide. In an alloy composition of about 12% aluminum the freezing begins at 575°C. and is complete at 436°C. As the composition approaches pure magnesium the temperature difference between the initial freezing and complete solidification decreases, and when pure metal is reached the liquidus and solidus lines coincide.

The area below the solidus, between the eutectic and pure metal, consists of two different structures. Between the eutectic point and the line marking the limit of solid solubility of aluminum in magnesium a heterogeneous mixture of eutectic and aluminum dissolved in magnesium occurs. Between the solid solubility line and pure magnesium a homogeneous solution of aluminum in magnesium forms.

It will be seen from Fig. 1 that about 2% of aluminum is probably soluble in magnesium at room temperature. Archer,⁴ by means of hardness determinations in aging experiments, concluded that the limit of solid solubility at room temperature is between 5 and 6%. Meissner⁵ states that an alloy of 7% aluminum is subject to age hardening while one containing 5% aluminum is not. Gann and Winston⁶ believed the solubility to be 6% or less at room temperature. A careful metallographic study of the line of solid solubility of aluminum in magnesium was made by W. Schmidt and Spitaler⁷ which indicated that about 7% aluminum is soluble at room temperature. Bakken and Wood corroborated this figure and Gann also, in general, agreed with the work of Schmidt and Spitaler.

Saldau and Zamotorin concluded after a metallographic study involving fairly long periods of annealing that the solid solubility of Al in Mg is 12.6% by weight at the eutectic temperature of 436°C. and 6.08% at room temperature. Although Saldau and Zamotorin found the solid solubility of Al in Mg did not change from

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room temperature to about 300°C., they considered this finding improbable from theoretical considerations and suggested the possibility that at low temperatures the precipitated particles are too small to be resolved under the microscope or that the annealing times selected were not long enough. This suggestion was verified by the work of Schmidt, Seliger and Siebel by means of precision measurements of the lattice constants. Also, Haughton and Payne by annealing a series of specimens for 32 days at 200°C. were able to resolve precipitated material in an alloy containing 3.88% Al and concluded that the solubility limit of Al in Mg at 200°C. is 3.58%. This is a fairly close check on the solubility found by Schmidt, Seliger and Siebel at this temperature. The X-ray method of investigation employed by Schmidt, Seliger and Siebel is often more accurate than metallographic and thermal methods as it is possible to detect, by measurements of the lattice, precipitated particles much smaller than can be detected by microscopic examination. These investigators worked with alloys in the form of extruded wire. After establishing the changes in the a and c axes caused by various amounts of aluminum in solid solution it was a simple matter to anneal specimens at definite temperatures for periods long enough to establish equilibrium, quench from the annealing temperature, and measure the a and c axes of the resulting solid solution. Reference to the curves established by plotting the lattice parameters against concentrations of aluminum in solid solution would then give the actual amount of aluminum in solution in the specimen in question at the annealing temperature used. It was found that the contraction of the a and c axes of the magnesium lattice is a straight line function of the atomic per cent of aluminum in solid solution. The a axis contracts from 3.201 Å units at 0% aluminum to 3.159 Å units at 11 atomic per cent aluminum, while the c axis contracts from 5.201-5.129 Å units. The ratio c/a is given as 1.625 for pure magnesium and 1.6286 for the alloy containing 11 atomic per cent aluminum in solid solution.

The vapor pressure of the magnesium rich aluminum alloys is comparatively high. For all practical purposes the vapor pressure of these alloys may be considered the same as that of pure magnesium. At compositions as high as 12% aluminum the vapor pressure at 700°C. is above 0.3 mm. of mercury. This forms the basis of a refining and scrap recovery process. Contrary to the work of Berry,¹⁰ who found that the compound MgZn₂ could be distilled without decomposition, there is no evidence that either the compound Al₂Mg₃ or AlMg₂ can be either distilled or sublimed as such. There is some experimental evidence indicating that under carefully controlled conditions of condensation the compound MgZn₂ does not distill without decomposition. Several years experience in refining magnesium scrap containing appreciable amounts of aluminum have shown that the magnesium content of the sublimate will not vary a great deal from 99.96%.

The electrical conductivity, temperature coefficient of resistance and thermoelectromotive force of magnesium-aluminum alloys have been studied by Pecheux⁴ and Broniewski.⁵ Mehl⁷ has also reported the temperature coefficient of resistance and thermoelectromotive force of a series of alloys containing from 31-50.25% magnesium.

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Constitution of Magnesium-Copper Alloys

By John A. Gann* and Manley E. Brooks*

Boudouard¹ was the first to investigate the magnesium-copper system and claimed to have identified three compounds (Mg_2Cu , $MgCu$, and $MgCu_2$) and four eutectics. Although his thermal analysis study was supplemented by microscopic examination and selective solution in dilute HCl, his work was somewhat sketchy and has not been completely verified by later investigators. Urasow² and Sahmen³ conducted thermal analysis studies over the entire magnesium-copper system and

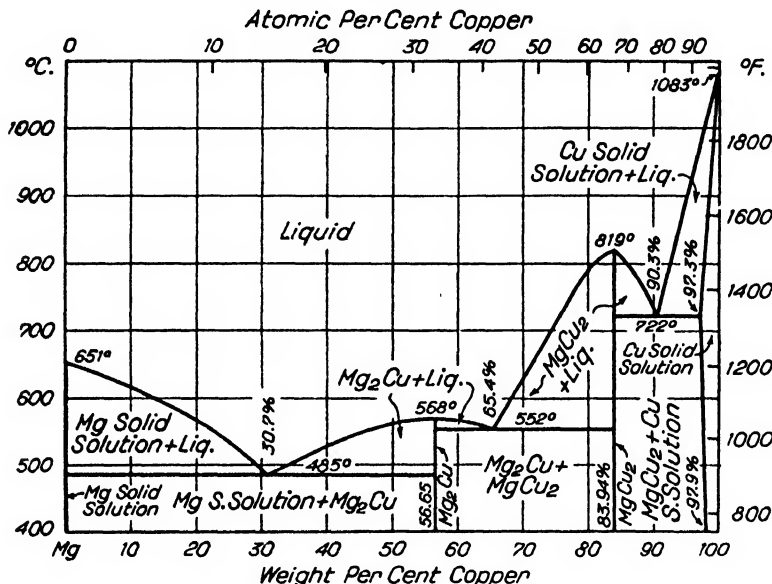


Fig. 1—Magnesium-Copper Constitution Diagram.

their results are in substantial agreement. Sahmen likewise examined these alloys microscopically. They identified the compounds Mg_2Cu and $MgCu$, but not Boudouard's reported compound $MgCu$. No solid solutions were reported by any of these investigators.

Stepanow⁴ determined the electrical conductivity of the magnesium-copper alloys at 25° and 100°C. and also the temperature coefficient of electrical conductivity. The results obtained were in good agreement with the diagrams of Urasow and Sahmen except for approximately 4% (10 atomic per cent) solid solubility of magnesium in copper. Stepanow felt that the earlier investigators had failed to find this solid solubility because of the low rate of diffusion in these alloys.

Based on metallographic examinations, Hansen⁵ concluded that 0.4-0.5% of copper is soluble in magnesium at 485°C. and less than 0.2% at room temperature. Jenkin⁶ conducted similar investigations and concluded that the solid solubility of copper in magnesium at room temperature was approximately 0.02%. Gann⁷ likewise showed that the solid solubility of copper in magnesium was low but made no direct determinations of the absolute value.

Runqvist, Arnfelt, and Westgren⁸ confirmed the existence of the two compounds Mg_2Cu and $MgCu$, by means of X-ray investigations. Grime and Morris-Jones⁹ made an X-ray diffraction study of the entire magnesium-copper system and confirmed the findings of Stepanow except for a range of solid solution extending (probably 2-3%) on both sides of the $MgCu_2$ compound, and for a 3% solid solu-

*The Dow Chemical Co., Midland, Mich.

bility of magnesium in copper as compared to Stepanow's 4%. No evidence was found of a solid solution of copper in magnesium, thus confirming Jenkin's low solid solubility limit rather than the higher values of Hansen.

Fig. 1 represents the most recent and also the most accurate constitutional diagram of the magnesium-copper system as constructed by Jones¹⁰ from thermal analysis and metallographic investigations. He confirmed the existence of the two compounds Mg_2Cu and $MgCu_2$, of three eutectics, and of solid solutions at either end of the diagram. Magnesium was shown to dissolve 0.03% of copper near the eutectic temperature and 0.02% at room temperature, while copper dissolves 2.6% of magnesium at 700°C. and 2.1% at room temperature. Jones was unable, however, to substantiate the findings of Grime and Morris-Jones relative to solid solutions on either side of the $MgCu_2$ compound and concluded that this compound does not form solid solutions with either magnesium or copper. The thermodynamic analysis of Jeffrey¹¹ is in complete agreement with the metallographic work of Jones, and shows that the liquid phase and the solid solutions have the simplest possible constitution, namely, monoatomic molecules of copper and of magnesium.

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Constitution of Magnesium-Manganese Alloys

By H. E. Bakken* and R. T. Wood†

General—The history of this alloy system is meager, most of the information available being obtained since 1927. No complete investigation of the equilibrium relations between magnesium and manganese has been made up to the time this is written and there is considerable doubt as to the exact constitution of these alloys. For instance, it is not definitely known whether the second phase that appears in the structure of alloys rich in magnesium containing from 1-3% manganese is a compound or metallic manganese. W. Schmidt¹ believes that it is an intermetallic compound but Gann² feels this phase is elemental manganese and points out that it occurs as "small blue gray particles scattered through the primary magnesium crystals, occasionally in clusters but seldom at the grain boundaries."

W. Schmidt states that as early as 1874 Terrell readily obtained a magnesium-manganese alloy by reducing manganese chloride with magnesium. The properties of the alloy obtained by Terrell were not described. Little else on the subject appears in the literature until 1921 when a patent on the process of making magnesium-manganese alloys was granted to W. R. Veazey.³ This process involved the reduction of manganese chloride in a bath of magnesium. Veazey stated that

alloys containing as high as 8% manganese can be obtained by this method. Alloys containing slightly more than 4% manganese have been made in the laboratory by direct alloying of metallic manganese with magnesium at a temperature of approximately 1100°C. under pressure in an atmosphere of argon.

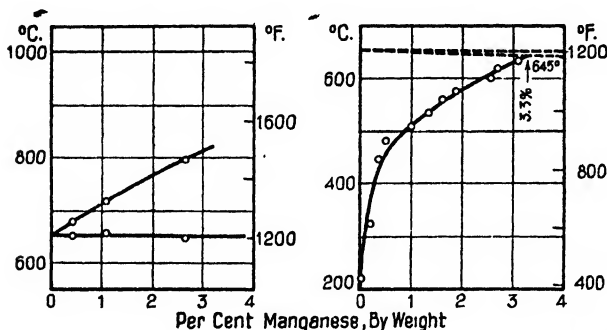


Fig. 1—Partial magnesium-manganese constitution diagrams. Left, by Ruhrmann; right, by Schmidt, Seliger and Siebel.

alloys containing as high as 8% manganese can be obtained by this method. Alloys containing slightly more than 4% manganese have been made in the laboratory by direct alloying of metallic manganese with magnesium at a temperature of approximately 1100°C. under pressure in an atmosphere of argon.

Solubility of Manganese in Magnesium—W. Schmidt examined the structure of alloys containing 1.1% manganese or less and could observe no eutectic or solid solution. Gann and Winston² state that manganese has only a limited solubility in the liquid state. Schmidt shows a diagram according to Joseph Ruhrmann indicating that the liquid solubility of manganese in magnesium falls from about 2.65% at 790°C. to about 0.5% at 675°C. The curve is extrapolated to show zero liquid solubility at the melting point of pure magnesium (651°C.). The alloy containing 2.65% manganese had a thermal arrest at 645°C.

Although W. Schmidt could observe no evidence of solid solution, Gann states that some manganese is present in solid solution and presents micrographs of cast alloys containing 0.1, 0.4, and 1.0% manganese that show a small amount of coring around the individual particles due to solid solution, which indicates the location of the manganese particles is closely associated with the original dendritic structure of the primary crystallization. Bakken and Wood found that as much as 3.2% manganese could be retained in solid solution and Pearson⁴ concluded that more than 2.7% manganese is soluble in the solid state.

X-Ray Evidence—The most recent and authoritative work on the solid solubility of manganese in magnesium is that of E. Schmidt with H. Seliger and G. Siebel.⁶ This investigation was made with the aid of a precision X-ray spectrometer. The solid solubility at 645°C. was established at 3.3% and decreases to practically zero at 200°C. These investigators also report that the lattice parameters *a* and *c* of the magnesium crystal are decreased linearly with increasing atomic percentages of manganese in solid solution.

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Construction of the Diagram—If the diagrams of Ruhrmann and E. Schmidt, Seliger and Siebel are correct, we have in this system a marked decrease in solubility under equilibrium conditions as the alloys containing from 0-3.3% manganese pass from the solid to the liquid state. Consider an alloy containing 2.2% manganese. At 644°C. this alloy would be a homogeneous solid solution but at a slightly higher temperature (about 650°C.) practically all the manganese would be precipitated and would not again be taken into solution until the temperature had been raised to above 770°C.

As it is impossible to construct a constitution diagram that will conform to the phase rule from the data of Ruhrmann, E. Schmidt, and others, the two diagrams are shown separately. The secondary arrests shown in the diagram according to Ruhrmann were found to exist by the present authors but not along the line drawn by Ruhrmann.

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Constitution of Magnesium-Zinc Alloys

By John A. Gann* and Manley E. Brooks*

Introduction—This article deals primarily with the magnesium-rich alloys. The zinc-rich alloys are discussed more fully in another article entitled "Constitution of Zinc-Magnesium Alloys".

Based on thermal analysis studies of alloys containing up to 8.55 atomic per cent of magnesium (3.36 weight per cent), Heycock and Neville¹ concluded that the lowering of the melting point of zinc was greater with the addition of magnesium than with any other metal tried. The first investigation of the entire magnesium-zinc system is attributed to Boudouard.² By means of cooling curves he proved the existence of the compound $MgZn$, and two eutectic minima, and assumed the formation of Mg_2Zn in an effort to explain certain microscopic and selective solution data. Grube,³ Bruni, Sandonnini, and Quercigh,⁴ and Eger⁵ confirmed the work of Boudouard except that they obtained no evidence of the existence of the compound Mg_2Zn . Gorbow⁶ thought that the eutectic between zinc and $MgZn$, constituted a new compound $MgZn_2$, but this opinion has not been confirmed. No solid solutions were observed by any of these investigators.

Electrical conductivity measurements by Stepanow⁷ substantiated the work of Grube; Bruni, Sandonnini and Quercigh; and Eger, except he found a solid solubility of a few per cent of magnesium in the compound $MgZn$. Smith⁸ pointed out that the steepness of Stepanow's conductivity curve in the low percentage zinc alloys likewise indicated the possibility of some solubility of zinc in magnesium. Electromotive force measurements by Kremann and Müller⁹ showed that magnesium was made more noble by the addition of zinc, probably due to the formation of a solid solution of zinc in magnesium. The electrical conductivity and metallographic work of Peirce¹⁰ confirmed the work of earlier investigators that no solid solutions were formed at the zinc end of the diagram. His associates, Anderson and Jillson,¹¹ reported later that magnesium was probably soluble in zinc to the extent of less than 0.002% at room temperature.

The determination of the solid solubility of zinc in magnesium has formed the basis of numerous investigations and much conflicting data. Stoughton and Miyake¹² concluded from their hardness and microscopic work that more than 10% zinc will dissolve in magnesium at the eutectic temperature and their aging experiments indicate that this solubility decreases to less than 5% at room temperature. Metallographic investigations by Schmidt¹³ showed that approximately 6% of zinc is soluble in magnesium at the eutectic temperature and 1.8% at room temperature. Tensile and hardness tests by Meissner¹⁴ conducted on alloys aged at various temperatures confirmed the perpendicularity of Schmidt's solid solubility curve up to 100°C. The absence of age hardening on a magnesium alloy containing 1.7% of zinc, as reported by Hansen,¹⁵ likewise confirmed the low temperature solid solubility. Metallographic studies by Chadwick¹⁶ indicated that the solid solubility of zinc in magnesium at the eutectic temperature was between 3.2 and 5.4 atomic per cent (8.2 and 13.3 weight per cent) and he assumed it to be about 5 atomic per cent (12.4 weight per cent). Electrical conductivity investigations by Grube and Burkhardt¹⁷ indicated that approximately 6.5% of zinc are soluble in magnesium at the eutectic temperature and 3.5% at 250°C. Schmidt¹⁸ stated that precision X-ray investigations gave 8.4%

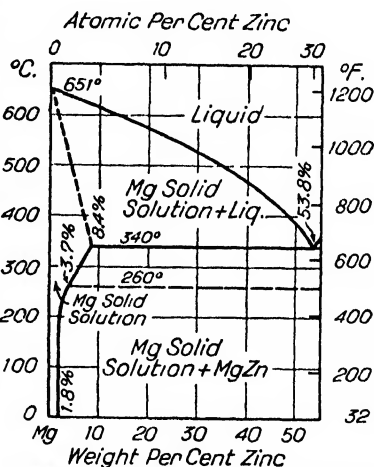


Fig. 1—Magnesium-Zinc Constitution Diagram.

*The Dow Chemical Co., Midland, Mich.

as the solid solubility of zinc in magnesium at the eutectic temperature and that this decreased to something over 1% at room temperature. Schmid and Seliger¹⁸ elaborated on this report and gave the solid solubility curve for the temperature range of 150-344°C. Schmid and Seliger, and Schmidt and Hansen are in excellent agreement on the solid solubility of zinc in magnesium throughout the temperature range of 150-250°C. Schmid and Seliger's value of 8.4% for the solid solubility of zinc at the eutectic temperature is appreciably higher than the corresponding value of Schmidt and Hansen, but is in good agreement with the lower value of Chadwick's 8.2-13.3% range and is substantiated by unpublished data from the laboratories of The Dow Chemical Company which indicate that approximately 8% of zinc is soluble in magnesium at the eutectic temperature.

The three most complete investigations of the magnesium-zinc system agree in most respects but differ chiefly in regard to the ability of the intermetallic compounds to form solid solutions. Chadwick¹⁸ in 1928 and Hume-Rothery and Rounsefell²⁰ in 1929 constructed constitutional diagrams based on thermal analysis and metallographic studies. The former reported solid solubility zones on both sides of the $MgZn_2$ compound and on the zinc-rich side of the $MgZn$ compound; while the latter concluded that neither compound entered into solid solution. Grube and Burkhardt¹⁷ in 1929 determined the electrical conductivity and thermal expansion of these alloys and confirmed the existence of the solid solubilities reported by Chadwick, and in addition claimed that the compound $MgZn_2$ formed a solid solution with excess of magnesium. Both $MgZn$ and $MgZn_2$ are formed by peritectic reactions and appear to undergo polymorphic transformations at somewhat lower temperatures.

Fig. 1 shows the constitution diagram of the magnesium-rich alloys according to Chadwick, modified to include the $MgZn$ compound reported by Hume-Rothery and Rounsefell, the polymorphic transformation of this compound at 260°C, as reported by Grube and Burkhardt, and the solid solubility of zinc in magnesium as reported by Schmid and Seliger near the eutectic temperature and by Schmidt and Hansen at lower temperatures. This portion of the diagram shows a simple eutectiferous system of alloys except for the solid solubility of zinc in magnesium and the polymorphic transformation of the $MgZn$ compound.

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Physical Constants of Magnesium

By Cyril S. Taylor* and Junius D. Edwards*

Atomic Weight—Magnesium has the atomic number 12. Its atomic weight is 24.32. The atomic volume is 14.0 cc. Magnesium has three isotopes; their mass numbers in order of the intensities of the mass spectrum lines are 24, 25, and 26.^{1, 2}

Crystal Form—Magnesium crystallizes with a hexagonal close packed lattice. The unit cell has the following dimensions^{3, 4}: The side of the hexagonal base "A" = 3.2030×10^{-8} cm., the height of the hexagonal prism "C" = 5.2002×10^{-8} cm. The axial ratio c/a = 1.6235.

Density—The density at 20°C. of magnesium of varying purity and form is given in Table I.

Table I
Density of Magnesium

Purity of Magnesium, %	Density at 20°C.	Form of Sample	Authority
99.99	1.7388	Extruded bar $\frac{1}{2}$ in. in dia.	(5)
99.99	1.7388	Same as above, but annealed 2.5 hr. at 400°C.	(5)
99.95	1.7381	Extruded bar $\frac{1}{2}$ in. in dia.	(5)
99.94	1.7386	Extruded bar $\frac{1}{2}$ in. in dia.	(5)
99.90	1.7381	Extruded bar $\frac{1}{2}$ in. in dia.	(5)
99.90	1.737	As cast	(6)

No change in density was observed as a result of annealing the purest metal for 2.5 hr. at 400°C. The density of 99.99% magnesium at and above its melting point has been determined by Edwards and Taylor.⁵ The values are given in Table II. The values given were taken from the complete density curve from 20-750°C.

The values for density are numerically equal to the specific gravity of the metal when referred to the weight of water at 4°C. Magnesium at 70°F. weighs approximately 108.5 lb. per cu.ft. (1.7388×62.428). In passing from the liquid to the solid state at the freezing point, there is a contraction in volume amounting to approximately 4.2%.

Table II
Density of Magnesium at and Above Its Melting Point⁵ 99.99% Purity

Temp., °C.	Density, g. per cc.	Remarks
650	1.642	At melting point, solid (calculated)
650	1.572	At melting point, liquid (extrapolated)
673	1.562	Measured
700	1.544	Interpolated

Table III
Average Coefficients of Expansion of Magnesium⁶

Temperature Range, °C.	Average Coefficients of Expansion per °C.		
	Cast Magnesium	Extruded Magnesium	Average
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$
20-100	26.1	25.8	26.9
100-200	27.8	27.6	27.7
200-300	29.7	29.5	29.6
300-400	31.6	31.5	31.5
400-500	33.6	33.4	33.4
20-200	27.0	26.8	26.9
20-300	28.0	27.8	27.9
20-400	28.9	28.8	28.8
20-500	29.9	29.7	29.8

Compressibility—The compressibility of magnesium or percentage change in volume with unit change in pressure of 1 megabar (0.987 atmospheres or 14,504 psi.) is approximately 2.9×10^{-6} at room temperature.⁷

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Thermal Expansivity—According to measurements of the Bureau of Standards by Hildner and Sweeney,⁸ the average thermal expansivity of cast and extruded magnesium (99.99% purity) is given by the following equation, for the temperature range 20-500°C., L_0 is the original length and L_t the length at temperature, t :

$$L_t = L_0 [1 + (24.80t + 0.00961t^2) 10^{-6}]$$

The average expansion coefficients for magnesium for a variety of temperature ranges are given in Table III.

Freezing Point—The value adopted by the Bureau of Standards⁹ for the freezing point of magnesium is 651°C.

Specific Heat—The specific heat is defined as the quantity of heat necessary to raise 1 g. of a given substance through a temperature of 1°C. Specific heat varies with temperature, and is usually expressed as a mean or average value over a definite range of temperature. The values for the mean specific heat of magnesium over several ranges of temperature are given in Table IV.

Table IV
Mean Specific Heat of Magnesium

Temp., °C.	Specific Heat	Authority
-190 to + 17	0.2048	Schlimpf ¹⁰
	0.2090	Behn ¹¹
-185 to + 20	0.2220	Nordmeyer and Bernoulli ¹²
-79 to + 17	0.2284	
	0.2311	Schlimpf
	0.2330	Brunner ¹³
-17 to + 100	0.2495	Behn
	0.2460	Brunner
	0.258	Voigt ¹⁴
150 to 250	0.258	Awberry and Griffiths ¹⁵
250 to 350	0.264	
350 to 450	0.280	
450 to 550	0.296	
550 to 625	0.300	
650 to 750 (liquid)	0.266	

Latent Heat of Fusion—The latent heat of fusion of magnesium, or the heat absorbed in converting a unit weight of the metal from solid to liquid at its melting point without changing the temperature is 46.5 g.-cal. per g. of metal (83.7 B.t.u. per lb.).¹⁶

Boiling Point—According to Hartmann and Schneider,¹⁶ the boiling point of magnesium is 1107°C. Leitgeb¹⁷ has determined the boiling point to be $1097 \pm 3^\circ\text{C}$.

Vapor Pressure—Vapor pressure values for magnesium at various temperatures are given in Table V. Millar's values are estimated from a boiling point of 1120°C.; Hartmann and Schneider's values are based on experimental observations.

Heat of Vaporization—The heat of vaporization of magnesium as determined by Musceleanu¹⁸ is 1700 g.-cal. per g. of metal (3060 B.t.u. per lb.). Values calculated by Richards,¹⁹ Johnston,²⁰ Hildebrand,²¹ and Hartmann and Schneider,¹⁶ range from 1300-1500 g.-cal. per g.

Critical Temperature—The critical temperature of magnesium, as calculated by Hartmann and Schneider,¹⁶ is 1867°C.

Table V
Vapor Pressure of Magnesium

Temp., °C.	Vapor Pressure Mm of Mercury	Authority
25	1.7×10^{-17}	Millar ¹⁷
300	2.5×10^{-8}	Millar
380	1.1×10^{-3}	Millar
651	2.28	Millar
750	12.	Hartmann and Schneider ¹⁶
800	26.	
850	49.	
900	94.	
950	166.	
1000	280.	

Table VI
Thermal Conductivity of Magnesium

Temp., °C.	Conductivity	Authority
0-100	0.376	Lorenz ²²
101-250	0.35	Williams ²³
18	0.376	Jones ²⁴
18	0.34	Archbutt ²⁵
18	0.38	Flusin, ²⁶ Maybrey, ²⁷ Guillet ²⁸

Thermal Conductivity—The thermal conductivity of magnesium is relatively high, being more than three times that of cast iron. The thermal conductivity of magnesium, or the amount of heat in gram-calories transmitted per second through a plate 1 cm. thick per sq. cm. of its surface when the difference of temperature between the two faces of the plate is 1°C., is given in Table VI.

Heat of Combustion—The heat of combustion of magnesium with oxygen was determined by Moose and Parr²⁹ and Franck and Hochwald³⁰ as 146,100 g.-cal. per mole ($\text{Mg} + \text{O} = \text{MgO}$), which is equivalent to 10,800 B.t.u. per lb.

Optical Properties—The reflecting power of magnesium has been determined by Coblenz³¹ and by Hulburt.³² Magnesium sheet, freshly cleaned in dilute hydrochloric acid, had a reflecting power for visible light of 82%, according to recent unpublished measurements by C. S. Taylor. Table VII gives the reflecting power of magnesium at various wave lengths.

Table VII
Reflecting Power of Magnesium

Wave Length $\mu = 0.001 \text{ Mm.}$	Reflecting Power, %	Authority
0.18 μ	10.0	Hulburt ³²
0.20	20.0	Hulburt
0.30	36.0	Hulburt
0.38	48.0	Hulburt
0.5	72.0	Coblenz ³¹
0.6	73.0	Coblenz
1.0	74.0	Coblenz
1.4	75.0	Coblenz
2.0	77.0	Coblenz
2.5	79.0	Coblenz
3.0	80.5	Coblenz
4.0	83.5	Coblenz
5.0	86.0	Coblenz
6.0	88.0	Coblenz
7.0	91.0	Coblenz
8.0	93.0	Coblenz
9.0	93.0	Coblenz

Electrical Resistivity, Conductivity—Some of the electrical properties of extruded magnesium rod are given in Table VIII. Magnesium has a volume conductivity equal to 38.6% of copper. The mass conductivity is 197.7% of copper.

The constant mass temperature coefficients of resistance for magnesium are given in Table IX.

Electrochemical Equivalent—The electrochemical equivalent for magnesium is the number of g. deposited per sec. by a current of 1 ampere or the g. per coulomb. It is equal to the atomic weight 24.32 divided by the valence 2, and the constant 96,500, or 0.12601 mg. per coulomb. In various units it is as follows:

Electrochemical Equivalent of Magnesium

Unit	Value
Mg. per coulomb.....	0.12601
Coulombs per mg.	7.9359
G. per ampere-hr.....	0.45364
Pounds per 1,000 ampere-hr.	1.0001
Ampere-hr. per lb.....	999.90

Electrolytic Solution Potential—According to standard terminology, magnesium is electronegative to the elements which it replaces in solution; the magnesium going into solution in the form of positive ions leaves the metal negatively charged.

Table VIII
Electrical Properties of Magnesium Rod
According to Taylor and Edwards

Description	Property	Value
Magnesium (extruded) 99.99%	Specific resistivity at 20°C.	4.4611×10^{-8} ohms/cm. ^a
Magnesium (extruded) 99.95%	Specific resistivity at 20°C.	4.4699×10^{-8} ohms/cm. ^a
Magnesium (extruded) 99.90%	Specific resistivity at 20°C.	4.4774×10^{-8} ohms/cm. ^a
International annealed copper standard	Volume conductivity compared with copper	100 %
Magnesium (extruded) 99.99%	Volume conductivity compared with copper	38.65%
Magnesium (extruded) 99.95%	Volume conductivity compared with copper	38.57%
Magnesium (extruded) 99.90%	Volume conductivity compared with copper	38.51%
International annealed copper standard	Mass resistivity	0.15328 ohm (m.g.)
Magnesium (extruded) 99.99%	Mass resistivity	0.07753 ohm (m.g.)
Magnesium (extruded) 99.95%	Mass resistivity	0.07768 ohm (m.g.)
Magnesium (extruded) 99.90%	Mass resistivity	0.07780 ohm (m.g.)
Aluminum, conductor grade	Mass resistivity	0.07640 ohm (m.g.)
International annealed copper standard	Mass conductivity	100 %
Magnesium (extruded) 99.99%	Mass conductivity	197.71%
Magnesium (extruded) 99.95%	Mass conductivity	197.33%
Magnesium (extruded) 99.90%	Mass conductivity	197.01%
Aluminum, conductor grade	Mass conductivity	200.70%

hence the characterization "electronegative". The single potential of magnesium (the normal hydrogen electrode being taken as zero and a solution being employed in which the metal ion concentration is normal) is very difficult to measure experimentally, and the results are not reproducible. Latimer,²⁸ from thermal data, has calculated the single potential of magnesium to be: $E^\circ = -2.40$ volts, a value which agrees fairly well with earlier calculated values.

Thermoelectric Power—The thermoelectric power of a circuit of two metals is the electromotive force produced by 1°C. difference in temperature between the junctions.

Table IX
Constant Mass Temperature Coefficients of Resistance for Magnesium
Smithsonian Physical Tables (1927)

Temp., °C.	Temp. Coefficient of Resistance	Authority
20	0.0040	Bureau of Standards
25	0.0050	Somerville
100	0.0045	Somerville
500	0.0038	Somerville
600	0.0100	Somerville

Table X
Thermoelectric Power of Metals with Respect to Magnesium
Calculated from Data in Smithsonian Physical Tables (In Microvolts per °C.)

Metal	0°C.	20°C	50°C.
Magnesium.....	0.00	0.00	0.00
Iron.....	-14.93	-14.17	-12.99
Gold.....	-0.58	-0.97	-1.55
Cadmium.....	-0.41	-1.45	-3.00
Copper.....	+0.88	+0.51	-0.06
Lead.....	+2.22	+2.03	+1.75
Aluminum.....	+2.98	+2.71	+2.31
Silver.....	+14.16	+14.98	+16.23

Note: The current flows in the magnesium from the hot junction to the cold when the sign is positive.

tions. Values of the thermoelectric power of metals with respect to magnesium are given in Table X.

Mechanical Properties.—The mechanical properties of pure magnesium, as given by American Magnesium Corporation, are shown in Table XI.

Table XI
Mechanical Properties of Pure Magnesium

Process of Manufacture	Condition or Heat Treatment	Tensile Strength, Psi.	% Elongation in 2 In.	% Red. in Area	Prop. Limit, Psi.	Psi. $\frac{1}{4}$ % Extension Under Load	Compressive Strength, Psi.	Psi. Shear Strength	Brinell 500 kg. Load 10 mm. Ball	Hardness Scleroscope
Casting (sand)	As cast	13,000	6	6	500	3000	32,000	14,000	30	20
Extrusion	As extruded	28,000	8	8	1000	6500	45,000	16,000	35	23
Rolling (sheet)	As rolled	25,000	4	5	2500	9500	14,000	40	31
Rolling	Annealed	25,000	5	6	2000	9000	14,000	33	27

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Properties of Magnesium-Aluminum Alloys (Containing Small Amounts of Manganese)

By R. T. Wood*

General—At the present time, aluminum is the most important element employed to form alloys of magnesium. Practically all of the commercial magnesium alloys manufactured in this country contain aluminum in amounts varying from 3-13%. Inasmuch as practically all commercial alloys of magnesium with aluminum contain small amounts of manganese, the data given in these pages applies to alloys containing manganese rather than pure binary magnesium-aluminum alloys.

The amount of manganese that can be retained in the alloys decreases with increasing aluminum content. Alloys with 4% aluminum usually contain about 0.35% manganese, while those with 12% aluminum usually contain about 0.10% manganese. The chief purpose in adding the manganese is to enhance corrosion resistance. It has little effect on the mechanical properties, although it does increase the proportional limit and yield strength of wrought alloys. Metallographically, the effect of the manganese constituent cannot be observed.

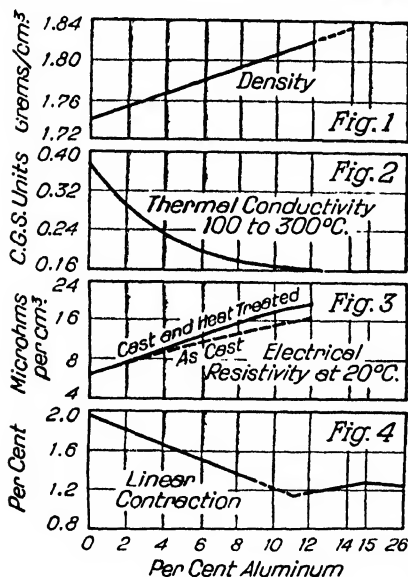


Fig. 1—Densities of magnesium-aluminum alloys. Fig. 2—Effect of aluminum on magnesium on the thermal conductivity. Fig. 3—Electrical resistivity of magnesium-aluminum alloys. Fig. 4—Linear contraction of magnesium-aluminum casting alloy.

show a precipitate when examined microscopically after such treatment.

The heat treatment of wrought magnesium-aluminum alloys is usually not beneficial unless more than about 9% aluminum is present, and in the range 9-13% aluminum, the solution heat treatment must be followed by artificial aging or precipitation to bring about maximum increases in tensile strength, yield strength, and hardness, which increases are at the expense of ductility. The increase in mechanical properties over those of pure magnesium brought about by the addition of aluminum and subjecting the alloys to a suitable heat treatment is remarkable. In the cast condition it is possible to triple the tensile strength, more than double the elongation, increase the yield strength seven times, triple the hardness

Because the solid solubility of aluminum decreases from 12.1% at the eutectic temperature to about 2% at room temperature, the magnesium-aluminum alloys are amenable to heat treatments involving solution and precipitation of the compound¹ Mg₂Al₃. From a practical standpoint heat treatment is most beneficial on alloys containing between 6% and 13% aluminum. All of the cast alloys in this range of composition are benefited by solution treatment, while those containing from 8% to 13% aluminum develop an appreciably greater hardness and a higher yield strength when the solution heat treatment is followed by a precipitation or aging treatment. From equilibrium data it might be expected that alloys containing from 2-6% aluminum would increase in hardness on aging at room temperature or at some elevated temperature in the range 200-300°F. However, such is not the case. An alloy containing 6% aluminum failed to show any change in properties after a solution heat treatment and room temperature aging for six years. Artificial aging at elevated temperatures for times up to 48 hours of alloys in the range 2-6% aluminum has failed to cause any worthwhile change in properties although alloys containing more than about 3.5% aluminum

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and more than double the endurance limit. In the wrought condition it is possible to double the tensile strength, triple the elongation, more than triple the yield strength, more than double the hardness and increase the endurance limit three and a half times. As the aluminum content of magnesium-aluminum alloys is increased above 5% in either the cast or wrought condition, they become less ductile until those with more than 13% aluminum are considered too brittle to use for structural purposes. When the aluminum content is increased to 30%, the alloy resembles glass in character.

Density—When aluminum is added to the maximum amount compatible with alloys of commercial usefulness (13%), the increase in density over that of pure magnesium is only about 6%. The densities of alloys in the commercially useful range are shown in Fig. 1.

Thermal Conductivity and Electrical Resistivity—The thermal conductivity of pure magnesium in the range 100-250°C.³ has been given as 0.35 in cgs. units. A more recent determination⁴ in the range 100-300°C. gives the value of 0.38 cgs. units. The addition of aluminum to magnesium progressively reduces the thermal conductivity in the manner shown in Fig. 2 until the 12% aluminum alloy has a thermal conductivity of only 0.16 cgs. units.

As would be expected in a series of alloys forming an appreciable range of solid solutions, the electrical resistivity of magnesium-aluminum alloys increases with increasing aluminum content. This relation for cast alloys and for cast alloys with all the aluminum in solution is shown in Fig. 3. A solution heat treatment causes a noticeable increase in resistivity especially in alloys containing 8-13% aluminum.⁵

Thermal Expansion—The coefficient of thermal expansion of pure magnesium in the range 0-100°C. is 0.0000259⁶ and this figure is not altered appreciably by the addition of aluminum in amounts up to 12%. There is some indication that the thermal expansion of wrought alloys is less than that of cast alloys. The value of the mean coefficient of expansion is apparently affected more by the temperature range selected for measurement than by the amount of aluminum present in the alloy. According to Scheel,⁴ the mean coefficient of linear expansion for magnesium, and hence the magnesium-aluminum alloys, from 0°C. to any temperature t may be obtained from the following equation:

$$\alpha = (25.07 + 0.00936 t) 10^{-6}$$

and the total length l_t at any temperature t may be expressed by the function:

$$l_t = l_0 [1 + (25.07 t + 0.00936 t^2) 10^{-6}]$$

Growth—In common with several other alloy systems wherein the solid solu-

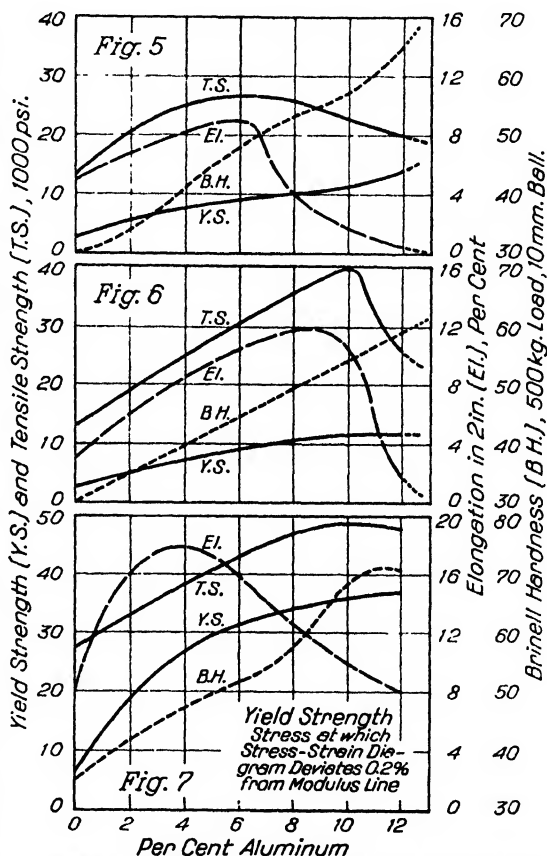


Fig. 5—Tensile strength of sand cast magnesium-aluminum alloy. Fig. 6—Same as Fig. 5, but after solution heat treatment. Fig. 7—Mechanical properties of extruded metal.

bility of the solute element decreases with temperature, the magnesium-aluminum alloys exhibit, under certain conditions, the phenomenon termed "growth". Alloys quenched from a high temperature solution heat treatment have a slightly higher density than the same alloys in equilibrium at room temperature. The magnitude of this difference is small under all conditions, but is greater the higher degree of supersaturation. This change in density is not noticeable or important until the alloys contain more than 8% aluminum in solid solution. Thus with ordinary sand castings the rate of cooling is such that for all practical purposes and especially for uses at room temperature, no changes in density can be detected.

However, in chill cast alloys and alloys containing 10-13% aluminum quenched from high temperatures, the change in density that may take place in service, especially service involving elevated temperatures of 300°F. or above, is noticeable and can be measured. Probably the greatest change in density is exhibited by the 12% aluminum alloy quenched from the solution heat treating temperature. Changes in density in this alloy have been estimated by measuring the linear change in dimensions accompanying reheating to elevated temperatures. This change in dimension has been termed "growth" or "permanent growth". The total unit growth of the quenched 12% aluminum alloy amounts to about 0.00074 in. per inch. Equilibrium is practically established by heating for 50 hr. at 440°F. In the chill cast 12% aluminum alloy the total unit growth is about 0.00043 in. per inch and in this case also, equilibrium is practically established by heating for 50 hr. at 440°F. In both cases, 30 hr. at 440°F. will bring about 85% of the total growth. There have been a few instances reported of growth in service of the solution heat treated 10% aluminum alloy but several years' experience indicates that for all ordinary conditions of service including use in aircraft motors, the amount of growth exhibited by the 10% aluminum alloy is unimportant.

Casting Characteristics—The magnesium-aluminum alloys have the best foundry or casting characteristics of any of the present well-known binary magnesium alloys with the possible exception of the magnesium alloys with copper. While the fluidity and freedom from shrinkage difficulties and hot shortness of the magnesium-aluminum alloys may not be any greater than that of the magnesium-copper alloys, their superior mechanical properties and resistance to corrosion and their amenability to heat treatment make the magnesium-aluminum alloys by far the most important series of alloys from the foundry's viewpoint. The properties of an alloy that determine its suitability for foundry use are fluidity, solidification shrinkage, linear contraction from solidification temperature to room temperature, and hot shortness. The fluidity of magnesium-aluminum alloys at casting temperature increases with increasing aluminum content. Although the fluidity of the best magnesium-aluminum alloy does not equal that of many aluminum-base casting alloys, it is adequate for most purposes. Tests have shown that under practical foundry conditions and when the metal is poured into green sand molds, a pouring temperature of about 790°C. is conducive to maximum fluidity. The total shrinkage from the molten state increases with the aluminum content up to about 7 or 8% aluminum and then decreases slowly. This increase in shrinkage is offset, so far as foundry characteristics are concerned, by a decreasing tendency to "pipe" as the amount of aluminum in the alloy is increased. One of the most important properties of alloys intended for foundry use is the linear contraction after solidification, as this property determines the pattern shrinkage that must be allowed and also has considerable influence on cracking. Fig. 4, according to Bastien,* shows the variation in linear contraction with concentration of aluminum of alloys cast in sand molds. Bastien found the linear contraction for alloys cast in chill molds to be somewhat less. The pattern shrinkage allowance on patterns built especially for use with the present commercial magnesium base casting alloys should be $\frac{1}{4}$ in., but, for most castings, patterns made for aluminum alloys with a pattern shrinkage of $\frac{1}{8}$ in. will be found to be quite satisfactory.

The other factor which, together with linear contraction, exerts a determining influence on the tendency of an alloy to crack when poured into a mold of complicated design is the property known as hot shortness. The hot shortness of magnesium-aluminum alloys increases with increasing aluminum content. In this series of alloys the tendency to crack because of stresses set up by contraction decreases as the aluminum content approaches 11% and then increases slightly while the tendency to crack because of low intergranular cohesion at elevated tem-

peratures increases steadily with increasing aluminum content. These two factors tend to counterbalance each other in alloys containing less than 11% aluminum, and hence it would be expected that at some composition under 11% aluminum, the tendency to crack would be at its minimum. Foundry experience indicates that this point lies within the range 8-11% aluminum.

Mechanical Properties—In the cast condition the addition of aluminum to magnesium brings about a marked change in all of the mechanical properties. Heat treating the alloys produces an even greater change. The variations in mechanical properties of magnesium-aluminum alloys with aluminum content in both the cast condition and after a solution heat treatment are shown in Fig. 5 and 6. Still other combinations of mechanical properties may be obtained by the artificial aging of heat treated alloys containing more than about 8% aluminum. The endurance limit of magnesium-aluminum alloys increases with increasing amounts of aluminum up to at least 10% aluminum. A solution heat treatment increases the endurance limit while artificial aging following the solution heat treatment reduces the endurance limit so that it approaches that of the as cast alloy. The endurance limit of a sand cast alloy containing 10% aluminum and given a solution heat treatment is about 11,000 psi. (500,000,000 reversals). The shear strength and compressive strength increase rapidly as the aluminum content is increased from 0-4%, but from 4% aluminum to about 10% aluminum the rate of improvement in these properties is reduced and, as the aluminum content is increased over 10%, the compressive strength and shear strength tend to drop somewhat. An average figure for Young's Modulus of Elasticity for magnesium-aluminum alloys containing up to 13% aluminum is 6,500,000 psi.

Working Characteristics—In common with other magnesium base alloys, the magnesium-aluminum alloys have poor cold working characteristics and hence all wrought products are produced by some hot working process. A certain amount of bending and forming may be done cold, and sheet and wire may be reduced by cold working interspersed with frequent annealing. Magnesium-aluminum alloys containing up to at least 20% aluminum may be extruded. The hot rolling characteristics of alloys containing more than about 8% aluminum are unsatisfactory, and in this country rolled magnesium alloy sheet usually does not contain more than 5% aluminum. The hammer forging characteristics of magnesium-aluminum alloys are poor but alloys containing up to about 10% aluminum may be worked comparatively readily on hydraulic or steam presses. Under carefully controlled conditions it is possible to hammer forge these alloys containing up to about 4% aluminum.

Magnesium-aluminum alloys are most readily fabricated by the extrusion process and it is by this process that the most favorable mechanical properties are obtained. Heat treatment of wrought magnesium-aluminum alloys is usually not beneficial although it is possible to increase the yield strength and hardness of wrought alloys containing from 9-11% aluminum by suitable treatment.

Mechanical Properties—The mechanical properties of extruded magnesium-aluminum alloys are shown in Fig. 7. The endurance limit of the wrought alloys increases with increasing aluminum content up to about 8 or 8.5%, after which it remains about the same or drops off slightly as the aluminum content is increased to 10%. The endurance limit of wrought alloys containing more than 10% aluminum has not been investigated. The endurance limit of thoroughly worked extruded material containing about 8% aluminum is about 16,000 psi. (500,000,000 reversals).

Corrosion Resistance—Magnesium-aluminum alloys containing the usual amounts of manganese are perfectly stable under ordinary conditions but are not suitable for use in direct contact with salt water. In seaboard atmospheres they should be protected with paint. These alloys are not subject to intergranular corrosion and, although attacked by nearly all acids and salt solutions they are resistant to alkalis and fluorides. In general, the resistance of magnesium-aluminum alloys to salt spray corrosion increases with the amount of AlMg₂ constituent in the microstructure. Heat treatment to bring about solution of this constituent reduces the corrosion resistance to salt spray. Aging supersaturated solid solutions to cause precipitation of AlMg₂ increases the corrosion resistance in proportion to the amount of precipitate. In order to increase their corrosion resistance, most magnesium alloys are dipped in a bath containing nitric acid and sodium dichromate which produces a surface that will resist tarnish for long periods and to which paint will

adhere. The use of inhibitive primers is very desirable and those pigmented with 100% zinc chromate have been found most effective. Synthetic resin enamels have been found to be the most satisfactory for the finish coats.

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Properties of Magnesium Casting Alloys

By John A. Gann*

General—Substantially all magnesium alloy castings are now produced from the Mg-Al-Mn or the Mg-Al-Mn-Zn alloys. (Die castings are generally made from a Mg-Al-Mn-Si alloy.) Aluminum is the chief added ingredient as it is more effective than any other element in improving the properties and casting characteristics of magnesium. Zinc is added in smaller amounts. It improves both the salt water corrosion resistance and the properties of the alloys, particularly in the heat treated condition. Manganese is present in all of these alloys in amounts ranging from 0.1-0.4%, that is, in amounts approximating the solubility of manganese in the liquid alloy. Manganese has little or no effect on the physical properties, but materially improves the corrosion resistance. The best combinations of properties are obtained with alloys containing 8-12% of aluminum, or of aluminum plus zinc. Alloys with less than 8% of added metal have relatively poor casting properties and low yield strength and hardness, while alloys containing more than 12% of added metal are too brittle for most purposes. The percentage of zinc must be kept relatively low in order to avoid hot shortness, particularly during heat treatment. Since copper and nickel have a deleterious effect on the corrosion resistance, all metal handling operations, particularly remelting, must be carefully controlled so as to keep these impurities at a minimum. The maximum quantities permitted by A.S.T.M. Specifications are 0.05% of copper and 0.03% of nickel.

The Mg-Al-Mn-Zn alloys are being widely adopted in this country now that they can be successfully heat treated: They bid fair to replace the older Mg-Al-Mn alloys because they offer better combinations of mechanical properties and improved corrosion resistance. The most widely used member of this series has a nominal composition of 6% Al, 0.2% Mn, 3% Zn, and balance Mg.

Nomenclature—The trade designation and society nomenclature of these alloys are given in Table I.

Heat Treatment—All of these magnesium casting alloys are amenable to heat treatment. Solution heat treatment increases the tensile strength, elongation, and impact toughness; while subsequent precipitation heat treatment, or aging, increases the yield strength and hardness at the sacrifice of the elongation and toughness. Properties intermediate between those obtained by solution heat treatment and those obtained by aging can be produced by a short time or partial precipitation heat treatment. This partial aging is not used extensively, however, because of practical difficulties encountered with furnace charges consisting of various sized castings with both thick and thin sections.

Properties—Average physical and mechanical properties of these alloys in the as-cast state and in the heat treated conditions most generally used are given in Table II.

Casting Characteristics—All of these magnesium alloys have good casting characteristics, although the technique employed differs somewhat from that used with other metals, particularly in the protective measures used in the melting and casting operations. Increasing the percentage of aluminum or of aluminum plus zinc tends to improve the fluidity. The low specific gravity of all magnesium alloys necessitates the use of generous runners and gates in order to insure proper feeding, and large risers to counteract shrinkage cracking. Pattern design calls for a shrinkage factor of $\frac{3}{8}$ in. per ft. on castings of moderate size, or $\frac{1}{2}$ in. per ft. on large castings and in those cases where normal shrinkage is hindered by bosses or internal cores. Generous fillets should be used where thin sections-join heavy sections and where the gates join the casting.

General Characteristics and Uses—Magnesium alloy castings are used chiefly in those industries where lightness and high strength-weight ratios are essential. They weigh two thirds as much as aluminum and approximately one fourth as much as iron; whereas their strength is comparable to that of aluminum alloys and varies from the same to approximately one half the corresponding values for cast ferrous metals, depending on the properties considered and the composition of the ferrous product.

*The Dow Chemical Co., Midland, Mich.

Table I
Composition, and Characteristics of Magnesium Casting Alloys

A.S.T.M. (B30-387) Alloy No.	United States Army	United States Navy	The Dow Chemical Co.	American Magnesium Corp.	Nominal Composition, %			Characteristics and Uses
					Al	Mn	Zn	
2	57-74-1B	.....	Dowmetal G	AM240	10.0	0.1	...	Remainder General purpose casting alloy; replaced largely by A.S.T.M. Alloy No. 4 in the various conditions.
3	.....	.....	Dowmetal B	AM246	12.0	0.1	...	Used in HTA* condition. Being replaced by A.S.T.M. No. 14 with higher tensile strength.
4	57-74-1B	M112e	Dowmetal H	AM265	6.0	0.2	3.0	Remainder Casting alloy with improved salt water resistance. Heat treatment not required for general use, but may be heat treated and aged to secure high strength and toughness or heat treated and aged to secure high yield strength with moderate toughness.
14	57-74-1B	.....	Dowmetal P	.....	10.0	0.1	1.0	Remainder For castings requiring highest yield strength and hardness and not subject to shock.

*Solution heat treated and aged.

Table II
Physical and Mechanical Properties of Magnesium Casting Alloys

Alloy No.	Condition	Sp. Gr.	Thermal Conduc- tivity	Elec- trical Resis- tivity	Tensile Strength,		Yield Strength		Elongation in 2 in.		Compressive Strength, psi.	Shear Strength, psi.	Brinell Hardness No.	Impact Izod, ft.-lb.	Fatigue Endurance Limit, psi.
					Typical	Specified Minimum	Typical	Specified Minimum	Typical	% Minimum					
2	S.C.	1.81	0.17	15.0	22,000	18,000	13,000	10,000	2	1	48,000	17,000	54	2	9,000
	H.T.	.....	.....	17.5	33,000	29,000	12,000	10,000	8	5	50,000	19,000	52	4	10,000
	H.T.A.	.....	.....	14.0	34,000	29,000	19,000	17,000	2	..	54,000	21,000	69	2	9,000
3	H.T.A.	1.81	0.16	14.0	29,000	27,000	20,000	20,000	0.5	..	54,000	18,000	78	1	9,000
4	S.C.	1.83	0.18	11.5	27,000	24,000	12,000	10,000	5	4	45,000	16,000	50	3	10,000
	H.T.	.....	.....	14.0	38,000	30,000	12,000	10,000	11	6	46,000	16,000	51	5	10,000
	H.T.A.	.....	.....	12.5	38,000	32,000	18,000	15,000	5	2	50,000	18,000	62	2	10,000
14	H.T.A.	1.82	.....	12.5	36,000	30,000	22,000	19,000	1	..	59,000	20,000	77	1	8,000

S.C.—Sand Cast. H.T.—Solution Heat Treated. H.T.A.—Solution Heat Treated and Aged.

Thermal Conductivity is expressed in cgs. units 100-300°C.

Electrical Resistivity is expressed in microhms/cm² at 20°C (68°F).

Tensile Properties are obtained on A.S.T.M. 1/2 in. dia. cast-to-size bars.

Yield Strength is defined as the stress at which the stress strain curve deviates 0.2% from the modulus line.

Compression and shear values are obtained on 1/4 in. dia. specimens machined from 1 in. dia. bars.

Fatigue endurance values are obtained on R. R. Moore machine at 500 million cycles.

Modulus of elasticity of magnesium alloys is 6,500,000 psi.

Minimum values conform to A.S.T.M. Specification B30-387 where applicable.

Excellent machinability is another valuable characteristic of magnesium alloys. They can be machined at higher tool speeds and with deeper cuts than is possible with other metals. Where machining costs constitute a large percentage of the total cost of the finished part, magnesium alloy castings often become strictly competitive with those produced from basically cheaper metals.

The aircraft industry is the largest consumer of magnesium alloy castings. The important applications include motor castings, starting equipment, instrument housings, landing wheels, and miscellaneous structural supports and brackets. The portable tool industry is using increasing amounts of sand castings for handles, motor cases, and gear housings in both electric and pneumatic drills and sanders. Magnesium castings are likewise used in the reciprocating and rapidly moving parts of textile, packaging, and conveying machinery or equipment as well as in fans, blowers, and rotors. Safety device equipment includes tongs, saw guards, and safety blocks for forming presses, and die cast goggle frames. Foundry uses include flasks, pattern plates, core boxes, and jigs. Die castings are finding many applications in office equipment and household appliances. Magnesium alloy castings are being used successfully in those industries where a saving in weight results in a more economical operation of the equipment or in a saving of human fatigue.

Polishing of Magnesium Alloys for Metallographic Examination

By R. W. James*

General—Metallographic preparation of the magnesium-base alloys requires a polishing technique quite different from that ordinarily employed on the harder ferrous and nonferrous alloys. Susceptibility to surface flow and scratching, and the tendency of abrasive particles to imbed in the matrix are characteristics of magnesium alloys that must be obviated as completely as practicable by a careful preparation of the samples. The procedure suggested develops a surface suitable for the production of high magnification (500 diameters, or more) photomicrographs.

There are several methods for mounting specimens that cannot be conveniently polished by holding in the fingers. One method is to place the sample face down on a glass plate, surround it with a ring cut from aluminum tubing of proper diameter, and fill the ring with molten sulphur, dental cement, or sealing wax. Mounting materials that may induce galvanic action during polishing or etching must be avoided. This mounting method provides sufficient edge-support for the specimen to materially facilitate the high magnification examination of edge effects such as corrosion, surface imperfections, fractures, or artificial coatings.

If the equipment is available, the metallurgical mounting press offers the most satisfactory method of preparing mounted specimens. A variety of mounting media, including Bakelite, Vinylite, Tenite, and Leucite, are commercially obtainable in a wide range of hardnesses and transparency. The mounting press method, by virtue of the heat and pressure employed, assures a more intimate contact between the specimen and the supporting medium, produces a mounting that will not chip off and foul the wheel and, by the proper selection of mounting media, results in a specimen mounting that permits maximum definition on a flat field.

A satisfactory method of preparing thin specimens for examination in cross section or inspection of surface films is to bolt a number of flat pieces together, using heavier retainer plates having about the same polishing characteristics as the specimens next to the bolt head and the nut.

The rough preparation of the specimens for polishing and the subsequent finishing operations are identical in all cases, irrespective of the mounting method.

Preparation for Microscopic Examination—The metallographic sample is removed from the article in question with a hand hack saw or by any other suitable method. Saw marks or other roughness on the face to be polished are removed with a "regular cut" file. The surface may be further improved by holding the specimen in the hand and drawing it several times over a "second cut" file held motionless on the bench by the other hand. This tends to eliminate the slight curvature that results from moving the file over the rigidly-held specimen. During the rough preparation of a sample, care should be exercised not to clamp the piece too tightly in the vise or subject it to unnecessary impacts that may produce mechanical twinning and subsequently lend confusion to the interpretation of the microstructure.

After the pieces are filed smooth, they are rubbed successively on No. 1, 00, and 0000 emery papers, the specimen being rotated 90° in passing to each finer abrasive to remove the scratches from the preceding paper. Magnesium and its alloys have little tendency to foul the papers but, should this difficulty be encountered, a small amount of kerosene poured on the paper will loosen the obstructing particles, promote a cleaner cutting action, produce a smoother specimen, and add appreciably to the life of the abrasive paper. The use of kerosene will also hold down the magnesium dust which may become objectionable if a large amount of grinding is being done.

If a microtome is available, and the blade is in good condition, rough-sawed metallographic specimens of magnesium alloys may be cut down to a plane surface suitable for taking immediately to the fine polishing wheels without the intermediate preparations recommended above.

Samples are taken from the No. 0000 paper, or the microtome, to a wheel covered with a fine quality broadcloth. In the first operation on this wheel, a dry abrasive known as 65F alundum (Al_2O_3) is sprinkled on the cloth and worked into a thin paste by the addition of water and manipulation with the finger tips. The wheel is then rotated at about 500 r.p.m. and the specimen applied to it until the scratches remaining from the previous operation are just barely removed. Too much

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pressure or excessive time in any of the finishing steps on the cloth wheels will cause the harder constituents (principally Mn and Mg₂Si) to stand out in undesirable relief. When the scratches have been removed, the cloth is washed free of abrasive and a good lather is worked up by holding a piece of soap against the rotating wheel. The speed is decreased to 300 r.p.m. and the specimen, held lightly against the cloth, is slowly rotated counter to the directional motion of the wheel. In this operation a high reflectivity should be developed by the removal or "washing out" of abrasive (alundum) particles embedded in the magnesium matrix. It is imperative that a high purity soap be used to prevent corrosive attack on the specimen. Ivory soap has been found quite satisfactory.

The final polishing wheel is covered with a high quality silk-velvet, closely woven, with an even warp and woof containing no coarse threads, and with short but full-bodied nap. The polishing compound should be a good grade of powdered magnesium oxide reagent. U.S.P. *heavy* magnesium oxide has been found superior to other grades. In the last operations, distilled water must be used exclusively, as the average tap water will not only enhance the formation of hard carbonate particles but will cause the specimen to "fog up" when it is finally removed from the wheel. A small amount of the oxide is placed on the velvet cloth with some distilled water and worked into the nap with the fingers. With the wheel revolving at about 150 r.p.m., the specimen should be held with considerable pressure on the cloth and slowly rotated several times counter to the motion of the wheel. The wheel is then slowed to about 100 r.p.m. and the pressure on the specimen decidedly decreased. Rotating the specimen slowly and under light pressure against the motion of the wheel for about one or two minutes should complete the final polishing. The wheel is then flooded with distilled water to wash the remaining polishing compound from the cloth and from the specimen and the pressure on the specimen is slightly increased for several seconds to complete the cleaning. The piece should then be quickly plunged into hot distilled water, immediately removed, and dried by sharply blowing on it. This method of drying has been found superior to rinsing in alcohol and drying in a warm air blast.

Magnesium oxide is preferred as the polishing medium on the velvet wheel because it is easily obtainable in a texture and quality that permits its direct use in the powdered form and eliminates the time consuming levigations or other refining and grading practices ordinarily required by other fine polishing abrasives. The objection to magnesium oxide lies in its tendency, under some conditions, to form hard particles of the carbonate. This tendency can be mitigated by keeping the powder dry until it is applied to the wheel, or by adding 50% glycerine to the distilled water used on the wheel. In the event that the cloth holding some magnesia is not used for a period of time and a few carbonate particles form, they may be effectively removed by boiling the cloth for several minutes in a 2% solution of hydrochloric acid, which will not affect the cloth.

After the polishing has been completed and the specimen blown dry, it is ready for examination under the microscope or for etching, as the case may be. Examination prior to etching is recommended when looking for cracks, porosity or other defects of a mechanical nature.

Etching of Magnesium Alloys for Metallographic Examination

By R. W. James*

General—Magnesium metallographic samples are usually etched to remove surface flow and reveal the true microstructure. Etching also outlines, attacks or colors the constituents in such manners as to aid in their identification.

Etching Reagents—A number of etching solutions have been recommended by various investigators who have worked with magnesium alloys. Many of the reagents and their specific applications have been reviewed in papers by Gann¹ and by Pulsifer². At present practically all metallographic etching in these laboratories is done with a preparation known as the "glycol etch." Its composition is as follows:

Diethylene glycol.....	75%	by volume
Distilled water	24%	" "
Concentrated nitric acid.....	1%	" "

The glycol etch permits a positive identification and separation of the constituents without severely attacking either the constituents or the matrix.

Some workers with magnesium prefer organic acid etches for grain boundary delineation in wrought alloys. Two of the suggested compositions are as follows:

For wrought magnesium-manganese alloys	For wrought magnesium-aluminum alloys
5 g. citric acid	5 g. malic acid (inactive)
95 cc. distilled water	2 cc. nitric acid (conc.)
	93 cc. ethyl alcohol

Etching Procedure—Pour a small quantity of the glycol solution into a beaker cover (watch glass). Holding the specimen upside down, either with the fingers or with tongs, immerse the polished face with a sliding motion. Do not drop it vertically into the solution. Do not allow the specimen to scrape the bottom of the beaker cover. After the surface is thoroughly wetted by moving the specimen back and forth several times, remove the specimen, turn it over, and blow lightly on the polished face to remove any gas bubbles that may form. An etching time of from 10-15 sec. is recommended for the average sample. Frequently the etching time can be correctly determined by watching the action on the specimen. As much as 30 sec. may be required to reveal completely the grain structure or coring effects in some specimens. When the desired action has taken place the balance of the etchant is removed by plunging the specimen either into a stream of hot water, or preferably, into a beaker of boiling distilled water. It is then dried by blowing sharply on the polished face.

It is suggested that the organic acid etchants, for grain boundary definition in wrought alloys, be applied by swabbing the specimen with absorbent cotton to prevent the etching product from depositing on the sample and obscuring the microstructure. Samples etched with the citric acid solution may be dried as described above. Those etched with the malic acid solution should be rinsed in warm water, immersed in acetone and dried in a warm air blast.

Identification of Constituents—It is recommended that an Eastman No. 78A filter, or its equivalent, be used on the microscope to convert the light to approximately daylight quality. The filter should be used with all arc and filament types of light source. The blue tint obtained aids materially in the separation and identification of the constituents.

Aluminum—Almost all commercial magnesium alloys contain aluminum as the principal alloying element. The magnesium-aluminum phase (the composition of which is somewhat controversial) in its primary condition occurs as a massive white material differing little in appearance from the matrix. The glycol etch sharply outlines the phase and reveals a definite relief as indicated in Fig. 1. The same phase when precipitated from solid solution possesses a lamellar structure quite

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similar in its appearance to pearlite of the iron-carbon system. A typical manifestation of the precipitate is shown in Fig. 1 and 4.

Zinc—The magnesium-zinc phase is similar in appearance and etching characteristics to the magnesium-aluminum phase. Practically all zinc-bearing commercial alloys also contain aluminum. In these alloys the aluminum and zinc combine with the magnesium to form a ternary magnesium-aluminum-zinc phase having essentially the same microscopic appearance as the binary magnesium-aluminum- and magnesium-zinc phases. Hence in commercial alloys the magnesium-aluminum-zinc complex will appear as the massive white constituent illustrated in Fig. 2. The micrograph also shows the lamellar precipitated phase of the ternary complex.

Manganese—All commercial magnesium alloys contain some manganese. The manganese constituent is generally spheroidal, has a pronounced relief and possesses a slate gray color. It is practically unaffected by the glycol etch, but is easily recognized because of its characteristic occurrence. Typical particles of this constituent are shown in Fig. 3.

Silicon—Silicon combines with magnesium to form magnesium silicide to the extent of the available silicon. If the silicon content is fairly high (1.0%) the compound usually develops the characteristic "Chinese script" formation illustrated in Fig. 4. With lower silicon concentrations the compound may occur as massive particles. The magnesium silicide is readily recognized by a powder blue to iridescent blue-green coloration which seems to be intensified somewhat by the glycol etch.

Tin—If the tin concentration is fairly high (6%) the magnesium-tin intermediate phase appears as shown in Fig. 5. It is colored either tan to brown or a dark blue by the glycol etch, the type of coloration depending on the length of time the specimen is etched. The etch clearly reveals coring effects in the as-cast alloy. If the tin concentration is lower than 6% and if aluminum is present the microstructure appears as illustrated in Fig. 6. The light colored constituent is the magnesium-aluminum phase. The dark particle is the magnesium-tin phase which possesses the etching characteristics described above. If the phase is massive there may be some color gradation in the individual particles.

Cadmium—At present there is only one domestic magnesium alloy containing cadmium. Under normal casting conditions the 3.5% cadmium in this alloy is retained entirely in solid solution, hence is not visible in the microstructure.

Conclusion—The micrographs represent the constituents and phases as they occur in as-cast alloys. The microstructures of some magnesium alloys will, of course, be considerably altered by thermal treatments but the etching characteristics of the constituents remaining in the microstructure will not be affected. Hot and cold working operations on magnesium and its alloys produce microstructural changes similar to those produced in other metals by comparable treatments. Mechanical working may refine the structures but will not obscure the identity of the constituents.

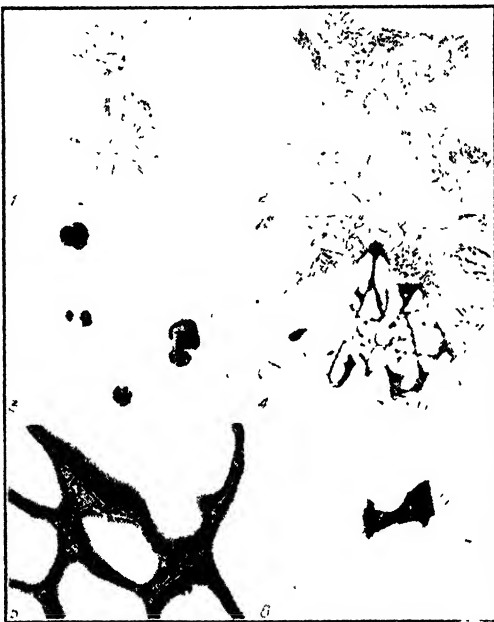


Fig. 1—Magnesium-aluminum constituent in alloy containing 10% aluminum

Fig. 2—Magnesium-aluminum-zinc constituent in alloy containing 6% aluminum, 3% zinc.

Fig. 3—Manganese constituent in alloy containing 1.3% manganese.

Fig. 4—Magnesium silicide in alloy containing 10% aluminum, 1% silicon.

Fig. 5—Magnesium-tin constituent in alloy containing 6% tin.

Fig. 6—Magnesium-tin and magnesium-aluminum constituents in alloy containing 3.5% aluminum, 5% tin.

(Original magnification 500 diameters in all cases)

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Magnesium Alloy Die Castings

By W. H. Gross*

Introduction—The advantages of magnesium alloy die castings are light weight, good mechanical properties, and excellent casting characteristics. Portable tools, typewriters, cameras, optical instruments, vacuum cleaners, goggles, motor rotors and parts, conveyors, recording instruments, and paint spraying equipment are a few of the applications.

The "well and plunger" type die casting machine is generally used. With this machine it is possible to obtain pressures of 5,000 psi., or even higher, resulting in castings of good strength and soundness.

Design—In many cases, dies designed for aluminum may be used for the production of magnesium alloy die castings, needing only to be adapted to the die casting machine. It is often desirable, however, to round off sharp corners and to increase fillets where these were too small in the original design.

The size of magnesium alloy die castings appears to be limited only by the size of the die casting equipment. At the present time, castings weighing 3 lb. and having a projected area of 200 sq. in. are in regular production. A conveyor part approximately 74 in. long has been die cast from magnesium alloy.

In general, the following tolerance limits apply. Closer tolerances may be possible in certain cases, depending upon the die design and the requirements of the user.

Variation from drawing dimension per in. length of solid die.....	0.0015 in.
Minimum tolerance limit within solid die.....	±0.003 in.
Minimum tolerance limit across parting line of die.....	±0.005 in.
Minimum wall thickness of casting.....	0.050 in.

Thicknesses greater than the 0.050 in. minimum above should not be less than A/1000 where A is the surface area in sq. in.

Minimum diameter of cored holes.....	0.062 in.
Maximum depth of cored holes.....	3 times diameter of hole
Draft of side walls per in. of length.....	0.010 in.
(Holes ¼ in. or less in diameter and less than ½ in. in depth will require no draft.)	

Alloys—Special alloys are used where certain property requirements or casting characteristics, not obtainable in the standard alloys, are desired. Table I gives the composition and mechanical properties of the magnesium alloys in regular use.

Table I
Mechanical Properties, Composition, and Characteristics of Magnesium Die Casting Alloys

Al	Composition, %			Tensile Strength, psi.	Yield Strength, psi.	Elong. in 2 in., %	Brinell Hardness	Impact Izod, Ft.-Lb.
	Mg, Balance	Mn	Si					
10.0	0.13	0.5	..	30,000	23,000	1	62	1
9.0	0.13	0.3	0.6	33,000	21,000	3	60	2
		max.						
8.0	0.15	0.3	..	32,000	20,000	3	60	2
6.0	0.2	0.2	..	27,000	17,000	4	50	3

Yield strength is defined as the stress at which the stress-strain curve deviates 0.2% from the modulus line.

Mechanical properties are obtained on standard A.S.T.M. die cast specimens.

Machining—Silicon carbide bakelite process discs have been found excellent where grinding is indicated since they cut well and do not load up. When finer grinding is required, instructions are given below under polishing and buffing.

One advantage of the die casting process is the ability to cast parts to relatively close dimensions, hence little machining is ordinarily required on die castings. When machining operations of any nature are necessary, complete instructions can be found in the article "Machining Magnesium," page 1601.

Finishing—Polishing and Buffing—Magnesium alloy die castings can be readily polished and buffed by the following procedures:

*The Dow Chemical Company, Midland, Mich.

Operation No.	Name	Abrasive	Wheel	Wheel Diameter, In.	R.p.m.
1	Polishing	No. 180 Emery	Glued felt, grease stick or dry	10-14	1800-2000
2	Buffing	No. 67 Tripoli	Unbleached sewed muslin buffs, 64-68 count	10-14	2000-2400
3	Coloring	Dry lime (Vienna) or No. 3 Crocus	Unbleached loose muslin buffs	10-14	2400-2700

Cleaning—After polishing or buffing and before further operations, magnesium alloy die castings should be cleaned according to the instructions given in the article, "Corrosion, Surface Treatment and Protection of Magnesium Alloys," on page 1611.

Chemical Treatment—Magnesium alloy die castings can be chemically treated to produce attractively colored decorative finishes or to provide a base for paint.

Colored finishes are produced on magnesium alloy die castings by treating the casting in a dilute solution of sodium hydroxide containing an organic dye. This operation is carried out in an autoclave at a temperature of approximately 390°F., which is obtained at a pressure of about 225 psi. By this process a great variety of durable colored finishes are obtainable. The luster of the finish is dependent upon the luster of the original casting. Sandblasting provides the only satisfactory surface for colored castings. If protection and not appearance is of prime importance, any mechanical cleaning will suffice.

The chrome-alum treatment provides magnesium alloy die castings with a black decorative finish, which also can be used as a base for paint for outdoor service. This treatment is applied by immersing the cleaned parts in a boiling solution of the following composition, until a black coating is obtained, usually about 10 min.:

Potassium chrome-alum ($K_2Cr_2(SO_4)_4 \cdot 24H_2O$)	4.0 oz.
Sodium dichromate ($Na_2Cr_2O_7 \cdot 2H_2O$)	13.3 oz.
Water	to make 1.0 gal.

Upon removal from the bath the parts should be rinsed thoroughly in fresh water followed by a hot water rinse to facilitate drying.

Properly applied coatings are smooth black and adherent, and are more easily secured on machined, sanded, or wire brushed surfaces. Loosely adherent brown powdery coatings result from depleted solutions which may be revived by small additions of sulphuric acid to maintain the pH of the solution between 3.5 and 2.5. Loose powder may be removed from the castings by wiping or by tumbling in sawdust.

The best base for subsequent paint coatings is obtained by the chrome-pickle treatment described in this Handbook in the article, "Corrosion, Surface Treatment and Painting of Magnesium Alloys," on page 1611. When treating die castings, the solution should be heated to 150°F. The time of treatment should be limited to approximately 5 sec., as a longer time results in the formation of a loose powdery deposit on the surface.

Enamels, Japans, and Lacquers—Before any organic finishing materials are applied to a magnesium die casting it must first be cleaned and chrome-pickled or otherwise treated as described above.

Baking finishes of the enamel and Japan types are ideal for use on magnesium alloy die castings. Speed of finishing, excellent adhesion, imperviousness to moisture, and wear resistance are some of the advantages of baked systems. The use of a primer is strongly recommended for all magnesium alloys. Under baking type materials, Naval Aircraft Factory iron oxide, zinc chromate primer P-23 baked 1 hr. at 250-300°F. has proved satisfactory.

Lacquer type materials have been used on magnesium alloy die castings, but they generally lack the adhesion and toughness found in baked systems. A baked primer or Naval Aircraft Factory zinc chromate primer P-27 can be used under lacquers.

The so-called novelty finishes provide a means of securing a number of unusual and attractive effects for the decorative finishing of magnesium alloy die castings. Through the use of these finishes crystal, crackle, granite, hammered metal, leather, marble, metal luster, mother-of-pearl, wood grain, wrinkle, and other interesting patterns are obtainable. The same baking or air drying primers described earlier can be used under the novelty finishes.

Hot and Cold Working of Magnesium and Its Alloys

By H. Menking*

General—Magnesium alloys harden rapidly with any type of cold work and therefore lend themselves to only small amounts of cold forming. At elevated temperatures, however, most magnesium alloys may be formed into intricate shapes without any trouble. Slow forming produces better results than rapid deformation.

Heating Methods—Equipment—With a few exceptions as indicated below, the proper working temperature is about 550-600°F. For moderate forming operations, temperatures down to 400°F. may be employed. The heating can be accomplished in several ways. The most simple is with a blow torch. While this method requires some control to avoid overheating the work, a little experience will soon enable the operator to handle the blow torch economically and safely to obtain satisfactory results. Heating to temperatures above 750°F. will only slightly lower the mechanical properties of the alloys, but above 800°F. the strength of the alloys is more seriously affected.

Other methods which require small initial investment but are considerably more economical in operation consist of preheating the part to be formed in an oven which may be gas, oil or electrically heated, or for temperatures up to about 530°F. by submerging it in an oil bath of 600W and holding for a few minutes prior to working. The working may also be done in a stream of hot air generated by gas or electric heating. The rapid rate of cooling of light gage magnesium sheet requires speedy handling after the sheet has reached the proper working temperature. Devices which keep the magnesium alloy hot during working, such as heated dies or hot air currents, are therefore often employed. With any method of heating, a blow torch should always be at hand to reheat the work when necessary. The type of heating to be selected in each particular case will largely depend on the operation to be performed and on shop conditions.

Temperature Control—There are several simple ways of controlling the temperature of the magnesium part and ensuring that it is within the proper working range: (1) An electric two-point contact pyrometer will ensure the quickest and most accurate temperature control and is recommended wherever possible. (2) A mark made with blue carpenter's chalk will turn white or light brown at the proper temperature. The chalk mark itself should not be exposed to the flame. (3) The application of a drop of 600W oil to the surface. The flash point will indicate the proper temperature. (4) A skilled operator will be able to judge the proper temperature, approximately, by the sound of the sheet when hammered. At the proper working temperature the sheet emits a dull or wooden sound which becomes more metallic as the sheet cools. (5) Ordinary newspaper formed into a ball and pressed for a moment against the magnesium part will turn to various shades from light yellow to dark brown depending on the temperature. A scale of different shades may readily be made up for comparison purposes.

Blanking and Shearing—In blanking or punching magnesium sheet or flat and thin extruded bar, the clearance between the die and the punching tool should, contrary to aluminum practice, be made as small as the accuracy of the stroke will permit without scoring. A clearance of about 0.015 in. (difference between the dia. of the punch and the die) or less, is recommended. The smoothness of the sheared surfaces increases with decreasing clearance. For good results in blanking and punching, the equipment must therefore be accurate enough to permit close clearances between tool and die. The use of hold-down pressures is recommended.

Heating to 500-600°F. will improve the finish of the sheared surface, and is especially recommended for sheet thicknesses above 0.060 in. and when using tool clearances larger than those recommended above. Allowance in the dimensional layout should be made for the expansion of the magnesium stock during heating. An additional means of improving the sheared surface is a slight rake (about 3°) on the punching tool. Fig. 1 illustrates the recommended practice.

In those cases where punching tools with large clearance are used and the stock is not warmed up for punching, the resulting rough surface must be dressed off to avoid conditions which may lead to failure in service. Rivet holes should be drilled rather than punched.

Mechanical shear blades should have square edges and as little clearance as possible. When hand shearing magnesium sheet, the sheer blade should not be

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completely closed after each cut as this may lead to small lateral cracks in the sheet at the end of each cut. For heavier gages, sawing the sheet is often preferable to shearing because of the better surface obtained.

Sheet-Bending—The minimum cold bending radius to which sheets may be subjected varies with the alloy, temper, thickness, and rate of deformation. Type of bending equipment and relation of the axis of the bend to the direction of sheet rolling also exert some influence on the results. Because of these factors the only

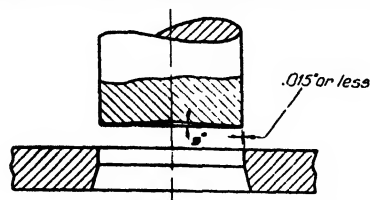


Fig. 1—Punching tool for magnesium sheet and plate

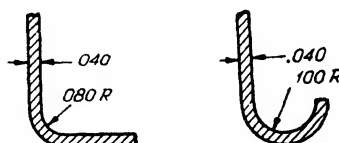


Fig. 2—Minimum hot bending radius for 90° and 180° bends.

safe criterion is to determine by actual trial the radius which is required or possible under the conditions of fabrication. Results of laboratory experiments under ideal conditions and recommended shop practice are given in the following table for sheet thicknesses of 0.040-0.060 in.:

Alloy	Minimum Cold Bending Radius for 180° Bends (In Terms of Sheet Thickness <i>t</i>)	
	Laboratory Determinations	Shop Practice
Pure Magnesium (hard).....	5 <i>t</i>	8 <i>t</i>
Pure Magnesium (soft).....	3 <i>t</i>	4 <i>t</i>
1.5% Mn Alloy (hard).....	5 <i>t</i>	8 <i>t</i>
1.5% Mn Alloy (soft).....	3 <i>t</i>	4 <i>t</i>
4% Al-0.4% Mn Alloy (hard)	5 <i>t</i>	8 <i>t</i>
4% Al-0.4% Mn Alloy (soft)	4 <i>t</i>	6 <i>t</i>
6% Al-0.3% Mn Alloy (hard)	5 <i>t</i>	9 <i>t</i>
6% Al-0.3% Mn Alloy (soft) ..	5 <i>t</i>	7 <i>t</i>

The radii in the first column were obtained in laboratory tests with relatively small pieces but experience has shown that it is difficult to duplicate these ideal conditions in actual shop practice. For sheet of less than 0.040 in. thickness smaller radii can be obtained, while larger radii will be required for sheet heavier than 0.060 in. A slight spring-back of the sheet must be taken into account when cold bending.

In hot bending, radii of about 2-2½ times the sheet thickness can be obtained in shop practice regardless of alloy or temper (see Fig. 2). For bending wide pieces of sheet in a brake, preheating in an oven is recommended as blow torch heating may result in an uneven distribution of the heat and lead to warping. Fair results are also obtained by clamping heated steel bars on both sides of the section to be bent. The steel bars will warm the magnesium sheet up sufficiently to permit bending. In either hot or cold bending a slow rate of deformation will give best results. Fig. 3 illustrates the proper way of bending short pieces of sheet by hand in the vise. The lining with round edges will prevent cracking of the sheet at the edge of the vise jaws.

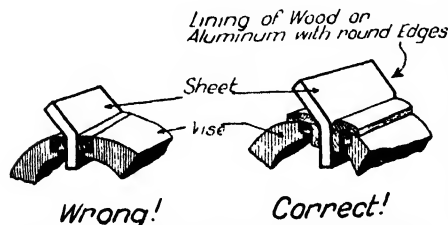


Fig. 3—Chucking in vise for bending small pieces of sheet.

alloy disc of 0.050 in. thickness and 20 in. dia. may be cold domed about 1 in. while a disc of the same dimensions in alloy 4% aluminum-0.4% manganese, will cold dome to about ½ in. However, in most cases the forming should be done hot, using one of the methods which follow:

(1) **Hand Forming Without Dies**—A simple method of hot forming consists of tightly clamping the edges of the sheet which is otherwise unsupported, and

Forming—A slight amount of forming, such as stretching or shrinking, may be done cold. For instance, a 1.5% manganese

hammering it into the desired shape with wooden, rawhide or rubber composition hammers. By frequent reheating with a torch, the sheet is kept in the working temperature range. For small work, a leather pillow, loosely filled with sand, may be used to support the sheet. The sand will give under the hammer blows and the deformation will be less severe. Wooden jigs are used to control the dimensions of the piece as the forming progresses.

(2) **Wooden Dies**—For more accurate work and greater economy, wooden dies can be used, provided the number of pieces to be formed is small. Wooden dies char at the temperature of working and are not suitable for quantity production. Concave dies are used for work of small size while convex dies are preferred for larger work. Often a combination of a convex die with a backing block is suitable, the latter being pressed down upon the work by means of a press or jack.

(3) **Aluminum or Magnesium Dies**—Slightly more expensive but more efficient and durable are aluminum or magnesium dies. Such dies are either made from a casting or a heavy plate. The latter has the advantage of a smoother surface while

a casting must be ground off smoothly before it can be used. Hot aluminum or magnesium dies preserve the heat better than wooden dies and avoid frequent reheating of the magnesium sheet. Magnesium dies do not hold the heat as long as aluminum dies do but are easier to handle due to their lighter weight. A burner may be arranged to keep the aluminum die at the proper working temperature. When using hot dies, it is frequently unnecessary to preheat the magnesium sheet as sufficient heat is imparted by the dies. Lubrication of the die surface is recommended. The actual forming is done with wooden hammers or hammers of soft materials as mentioned under (1). Fig. 4 illustrates this method.

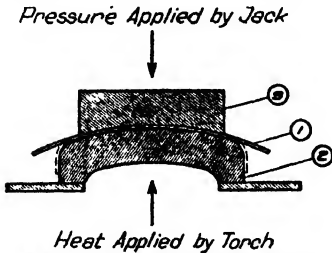


Fig. 4—Die forming of a disc of magnesium alloy sheet. 1. Magnesium alloy sheet. 2. Die (aluminum or magnesium). 3. Backing block (aluminum or magnesium).

presses are most suitable. Lubricated and heated dies are essential factors in this type of forming and the rate of deformation should be as slow as possible. Single or double action presses can be used for light draws. For more severe forming, hydraulic presses are preferred, although single or double action presses may also be used with reduced speed. Often the drawing is done in two or more steps, requiring the corresponding number of dies. In this type of work, the proper temperature for the 4% aluminum-0.4% manganese alloy is approximately 450°F. with a range from 300-600°F. For the 1.5% manganese alloy, a temperature of about 600°F. is recommended.

Drawing of Sheet Profiles—Flat strips of magnesium sheet may be drawn into profiled shapes. This method of producing profiled shapes is used for wall thicknesses below approximately 0.060 in. which cannot easily be obtained by extrusion. The strip is preheated in an oil bath and then drawn through two dies, the first serving to produce a shape approaching the desired profile while the second die produces the final shape. The oil bath serves as heating element and lubricant. The dies are made from magnesium extruded bar, which reduces the die costs. An example of the drawing steps involved is shown in Fig. 5.

Spinning—Magnesium alloy sheet is suitable for spinning if the work is kept hot while it is mounted in the spinning lathe. Only small amounts of spinning may be done cold. The heat is applied by a blow torch and the temperature should be about 400-600°F. Ordinary laundry soap will ensure fairly satisfactory lubrication but the mixture of mutton tallow and paraffine wax described below is preferred. At the proper temperature, the lubricant film will assume a dark brown glossy appearance. Care should be taken to avoid overheating the sheet although this danger is not great due to the rapid rotation of the work. Depending on the severity of the deformation, an r.p.m. of 300-450 is recommended in spinning discs of 15-25 in. dia. The edge of the sheet should be filed clean before starting to reduce

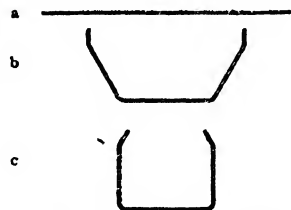


Fig. 5—Drawing of sheet profiles. a. Sheet strip. b. Intermediate shape. c. Final shape.

the risk of edge cracks. Wooden chucks are suitable for a few pieces, but cast aluminum or magnesium chucks are more durable at the temperatures involved and are recommended when spinning fair quantities. Fig. 6 shows spinning samples of 0.051 in. 4% aluminum-0.4% manganese soft sheet.

Bead Rolling—Beads may be rolled into magnesium sheet if the latter is heated. A simple way is to preheat the sheet with a blow torch or preferably in an oven and arrange a blow torch in front of the bead rolls in such a way that, before reaching the rolls, the sheet is heated to the proper temperature. Unless the beads are very shallow they should be rolled in several passes. Liberal radii, slight lubrication, and a slow rate of deformation should be used.



Fig. 6—Spinning of a cup shaped part of 13 in. dia. from 0.051 in. thick sheet.

jected to bending and forming operations to the same extent as the original sheet.

Extruded Shapes—Minimum Bending Radius—Extruded shapes must be heated for bending, unless the bending radius is comparatively large. In view of the wide variations in section and alloy, only general recommendations can be made. The approximate rating of the different alloys as to bending properties is given in the following table in which the group 1 designates the best bending characteristics:

1. Pure Mg, 1.5% Mn Alloy, 4% Al-0.4% Mn Alloy, 3% Al-1% Zn-0.4% Mn Alloy.
2. 3% Al-3% Zn-0.3% Mn Alloy, 6.5% Al-0.75% Zn-0.3% Mn Alloy, 6.5% Al-1.25% Zn-0.3% Mn Alloy.
3. 8.5% Al-0.5% Zn-0.2% Mn Alloy, 10% Al-0.2% Mn Alloy.

Alloys of group 3 take only a small amount of cold bending, and heating reduces their elongation to 2-3%.

A minimum cold bending radius (180° bends) of about 8-10 times the thickness may be used as a guide for $\frac{1}{4}$ in. thick flat extruded bar in the 4% aluminum-0.4% manganese alloy, and 10-15 times for the 6.5% aluminum-0.75% zinc-0.3% manganese alloy. More intricate shapes, such as Tees, require larger cold bending radii.

The minimum hot bending radius (180° bends) for $\frac{1}{4}$ in. thick flat extruded 4% aluminum-0.4% manganese bar is about twice the thickness. For more intricate sections, the minimum hot bending radius should be determined by actual trial.

Bending Equipment—Ordinary profiled steel bending rolls may be used for cold bending extruded shapes. Commercial tube bending machines equipped with proper tools to bend shapes are also suitable. A lubricant is used with the latter. For hot bending, these methods may also be employed, using heated tools. The use of aluminum or preferably magnesium alloy tools will allow rapid heating. When bending rolls or tube bending equipment are not available, either of the following two methods, requiring only inexpensive equipment, may be used:

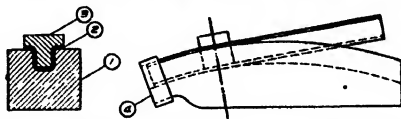


Fig. 7—Bending of channel section.
1. Die (wood, aluminum, or magnesium).
2. Channel section to be bent. 3. Back-up block. 4. Clamp.

(1) **Cast aluminum or magnesium blocks, heated to about 600°F.**—Fig. 7 shows the blocks used for a channel section. In the case of Tee and similar sections, the block (1) may be split to facilitate removing the web from the slot in the block. The magnesium section is clamped down tightly at one end and then gradually hammered down into the slot by means of a wooden hammer. If wrinkles develop, they are straightened out by hammering after completing the bend. Wooden blocks are suitable for making up a small number of samples, but not for larger quantities as the torch flame will gradually char the wood.

(2) **Profiled Rolls**—A magnesium shape may be bent around a stationary profiled roll of the desired bending diameter, the bending being accomplished by slowly rotating a small roll along the periphery of the big roll from position A to B, as shown in Fig. 8. A flat shape $\frac{1}{4}$ in. x $1\frac{1}{2}$ in. may thus be bent over its narrow side around an 8 in. radius.

Tubing—Magnesium alloy tubing is readily bent on commercial tube bending machines. Cold bending is possible with thin walls and ample radii. More severe bending is done at temperatures from 500-700°F. The tube is filled with fine dry sand to prevent it from flattening. When hot bending, the sand is preheated with the tube and serves to preserve the heat. Steel balls of the exact inside diameter, strung on a cable and inserted into the section to be bent, can also be used to prevent flattening. If a tube bending machine is not available, wooden or cast light metal blocks such as those described for bending extruded shapes, may be used. A small wooden block fitting the outside of the bent tube should be employed as an intermediary tool between the tubing and the hammer used for the bending. Magnesium alloy tubing may be shouldered by spinning. The proper temperature varies from 300-450°F. The recommended r.p.m. of the spinning lathe is from 200-400. Soap is used as lubricant.

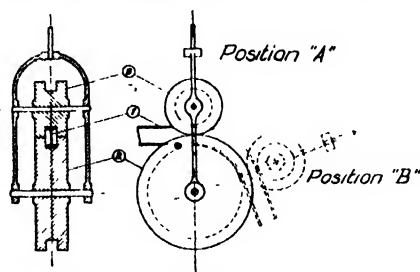


Fig. 8—Roll for bending extruded shapes
1. Shape to be bent. 2. Stationary roll. 3. Rotating roll.

Lubricants—C-Metal oil is used for light draws which are performed cold. For difficult draws which are done at elevated temperatures, lard oil or 600W oil is recommended. A mixture of two part of rendered mutton tallow and one part of paraffine wax may also be used. This mixture is prepared by melting, pouring into bricks and rubbing against the blank before drawing.

Machining of Magnesium and Its Alloys

By H. Menking*

Tools—Machining tools of standard design as used for other metals may, in most cases, be employed for magnesium. For maximum economy, however, these tools should be of slightly different design. The main factors governing the design of tools for cutting magnesium are (1) the extremely low cutting resistance, (2) the comparatively low heat capacity of the metal, and (3) the large volume of the chips obtained due to the easy cutting. The low cutting resistance leads to high speeds and heavy feeds and the problem is to dispose of the chips quickly and smoothly without jamming and subsequent development of frictional heat. The low heat capacity tends to create higher temperatures in work, chip and tool under conditions of friction as compared with other metals. These basic factors lead to tools with the following principal characteristics: (1) Smooth tool faces. (2) Large peripheral clearances. (3) Large chip spaces and (in milling cutters) small number of blades. (4) Small areas of the tool in contact with the work. (5) Comparatively small rake angles (undercuts).

In grinding the tools, it is most essential to keep the cutting edge as keen and smooth as possible and free from grinding wheel scratches, burrs or wire edges. In addition, the tools should be kept as smooth as possible wherever they come in contact with the chips in order to facilitate chip flow. Keen tool edges and smooth tool surfaces are best obtained by finish grinding on a fine or very fine abrasive wheel followed by a careful hand stoning with a fine or extra fine oil stone. Tools pre-

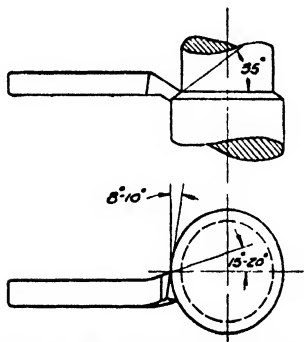


Fig. 1—Lathe tool for roughing

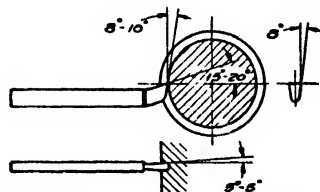


Fig. 2—Lathe tool for parting.

viously used for other metals should always be resharpened before cutting magnesium regardless of whether the cutting angles are changed or not.

Tools tipped with tungsten carbide give considerably better results than high carbon or high speed steel tools. They are recommended for maximum efficiency especially in cases where extremely high cutting speeds are employed. The higher price of these tools is more than offset by their longer life, greater accuracy and greater operating economy due to less frequent resharpenings.

Turning—Fig. 1 shows a recommended lathe tool for rough cutting. The large clearance (8-10°) and the small top rake (15-20°) are important. A larger top rake will often cause feeding of the tool into the work. In some machine shops, no top rake is used, which assists in breaking up the chips and prevents curling. Such a tool, however, is not generally recommended since it slightly reduces the smoothness of the machined surface and tends to increase the power consumption. The side rake may vary from 0 to about 10°.

The recommended finishing tool differs from the roughing tool by having a round nose (.040 in. dia.) on the tool tip, producing a smoother finish to the surface. As compared with aluminum it has been general experience that narrower tool noses are sufficient to obtain the same degree of smoothness.

Form tools (broad nose tools) for taking wider cuts or turning specially shaped contours should be designed along the same lines, except that the top rake should

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be reduced to about $3-8^\circ$ to avoid chattering. Fig. 2 illustrates a parting tool. The large clearance angles are important to reduce friction and to avoid breakage of the tool.

Planing and Shaping—In principle, the same cutting angles are used as for lathe tools.

Milling—Milling cutters for magnesium should be of the coarse tooth type. They should have considerably less, preferably only one half or one third, as many teeth as is standard with conventional cutters used for iron and other metals. The

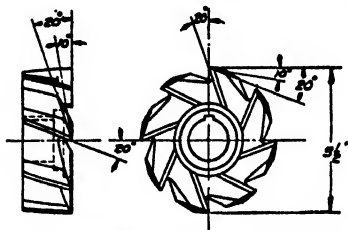


Fig. 3—Face Mill.

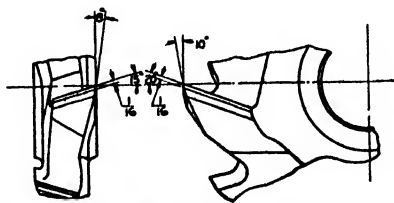


Fig. 4—Staggered tooth cutter—recommended design of tooth.

larger chip space and the heavier cut resulting from the smaller number of teeth lead to a reduction of frictional heat and to greater chip clearance and consequently to higher speeds, decreased tendency to distortion, lower power consumption and smoother finish. Unless otherwise stated, a primary peripheral clearance of 10° , $\frac{1}{16}$ in. wide, followed by a secondary clearance of 20° is common to all cutters illustrated.

Solid Cutters—Fig. 3 shows a recommended type of face cutter. Fig. 4 illustrates a 6 in. dia. staggered tooth (slotting) cutter with 12 teeth. A helix angle of 15° , an undercut of 20° and an 8° clearance on the side of the tooth are suggested for the latter type of cutter. Plain mills (Fig. 5) are recommended with 25° undercut and 45° helix angle. On form cutters (Fig. 6) the undercut is reduced to $5-8^\circ$ due to the heavier cutting pressure. A larger undercut may result in chattering.

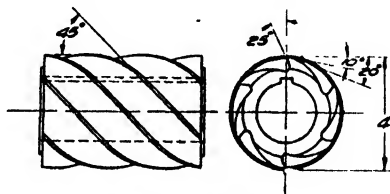


Fig. 5—Plain mill.

Inserted Blade Cutters are less expensive than solid cutters of large diameters and offer a better chance to obtain large chip space. They are therefore used for high peripheral speeds. Fig. 7 shows the design of an 8 in. dia. inserted blade face mill with 6 to 8 blades. The blade design of an 18 in. dia. cutter as used for extremely

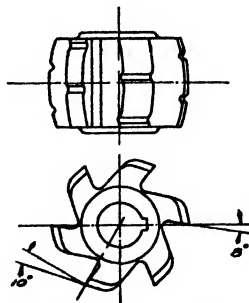


Fig. 6—Form cutter.

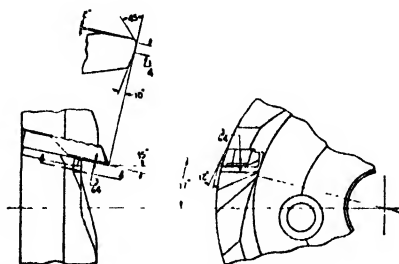


Fig. 7—Inserted blade face mill—recommended design of blade.

high cutting speeds (5,000 ft. per min.) is shown in Fig. 8-9. Particular attention is called to the unusually small number of blades, the free unobstructed chip space between cutter body and work, the curved out and polished face of the blade and

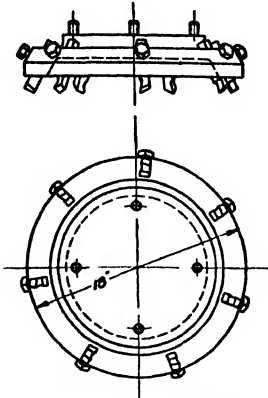


Fig. 8—Inserted blade face mill for extremely high speeds.

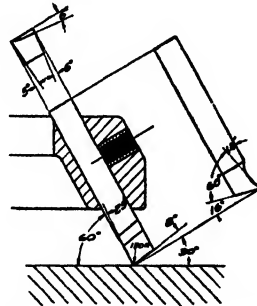


Fig. 9—Design of blade of inserted blade face mill shown in Fig. 8.

the large clearance (16°). All of these features aid chip flow and reduce friction and will therefore make higher cutting speeds possible and increase the life of the teeth.

A suitable type of shell-end cutter is shown in Fig. 10. It is designed along the same lines as the milling cutters described before.

Cutting Speeds and Feeds in Milling and Turning—With the type of machining equipment now used as standard, magnesium alloys may, under ordinary conditions, be machined at maximum spindle speeds and with feeds and cuts up to the capacity of the machines.

Speeds—Peripheral cutting speeds of 5,000 ft. per min. have occasionally been used in milling magnesium alloy castings, taking $\frac{1}{4}$ in. cuts and feeds of 0.045 in. per revolution in roughing, and 0.004 in. cuts and feeds of 0.015 in. per revolution in finishing. While such speeds are still considered exceptional, speeds of 1,000-3,000 ft. per min. in milling and turning magnesium are standard practice in many machine shops. Due to limitations in the spindle speed, such speeds can, in milling, be obtained only with large diameter cutters, or in turning, with castings of large diameter. With a given maximum spindle speed, the diameter of the milling cutter is often enlarged in order to increase the peripheral speed when changing from aluminum to magnesium castings. Magnesium castings are not dynamically unbalanced to the same degree as are parts of a heavier metal. This will tend to reduce the force of possible vibrations and allow higher cutting speeds. Milling cutters with magnesium bodies have been developed for extremely high speeds in order to reduce or eliminate vibration.

Feeds and Cuts—The highest feed that can be attained within the capacity of the available equipment may in most cases be used for roughing. In cases where mechanical feed is too slow, hand feeding is often resorted to in order to increase the machine output. Roughing feeds up to 0.080 in. per revolution have frequently been used. In finishing, where the smoothness of the surface is the controlling factor, a better surface can be obtained with the same feed, and an equally smooth surface with a greater feed when machining magnesium as compared with aluminum alloys. Frequently a special finishing operation is unnecessary due to the smooth finish obtained in roughing. Cuts of $\frac{1}{4}$ in. and more may be taken with the proper tools and with rigid chucking. With a machine of 5 hp. capacity, a cutter of suitable design will take $\frac{1}{4}$ in. cuts with feeds of 15 in. per min. (0.035 in. per revolution) and peripheral cutting speeds of 900 ft. per min. The use of greater feeds actually results in a reduction of frictional heat and in freer cutting. It has been observed at times that the work becomes quite hot and the chips jam the cutter when using low speeds and feeds, whereas free cutting and low temperatures will be obtained when the speed and feed are increased.

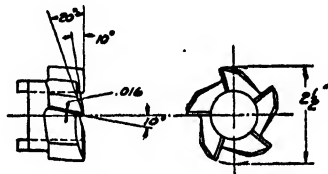


Fig. 10—Shell end cutter.

Limiting Factors—The following factors tend to limit the use of high speeds and feeds:

- (1) Dull tools, or ones of incorrect design (too small clearances, insufficient chip space) will cause frictional heat and warping.
- (2) Magnesium alloys will sometimes, due to their lower elastic modulus, require more rigid chucking than aluminum alloys to avoid chattering when maximum speeds are to be used. Where this is impracticable the speed and feed must be reduced.
- (3) The shape and design of the work may limit the cutting speed. If a casting with light and thin sections is machined at high speeds, the spring of the metal and the resulting vibration may result in chattering and inaccurate dimensions. More rigid chucking or reduced speed and feed will help to improve such a condition.
- (4) Fine or light feeds will sometimes generate frictional heat which may result in distortion and inaccuracy of dimensions. In combination with dull or improperly designed tools and high cutting speeds, they may occasionally lead to the ignition of fine shavings. While this condition can be controlled by the use of coolants and lubricants, the general rule should be to avoid extremely light feeds where possible.

Reaming—For reamers for magnesium, a small clearance (3-4°) and a small undercut (5-6°) is recommended in order to secure a steady cut without vibration. A recommended type of solid expansion reamer is shown in Fig. 11. The special steel and diamond boring tools often used for reaming are well suited for magnesium.

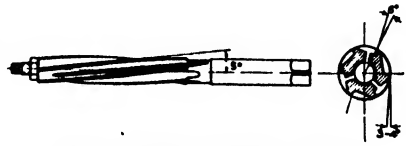


Fig. 11—Solid expansion reamer

Drilling—Two different types of twist drills are recommended, depending on the depth of the hole to be drilled.

Deep Holes—A drill for deep holes (more than about four times dia.) should have a spiral angle of about 40°, a parallel web and smoothly polished flutes in order to ensure rapid flowing of the chips. The clearance (relief behind land) should be twice as deep as with standard drills. The land (or margin) should be narrower than customary ($\frac{1}{2}$ of standard width). A point angle of 110-120° and a lip clearance of 15° is recommended. A drill of this design will cut freely and will readily clear out the chips. Raising the drill to remove the chips will be unnecessary unless the hole is deeper than about 15 times the dia. A drill of suitable design is illustrated in Fig. 12.

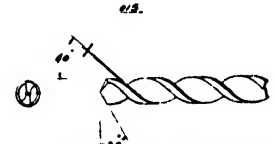


Fig. 12—Drill for deep holes.

Too close a distance between the drill jig bushing and the surface of the drilled part will prevent the chips from flowing out readily and will cause them to jam in the flutes. An approximate minimum distance of $1\frac{1}{2}$ times the hole diameter is recommended.

Short Holes—The main feature of a drill for short holes (less than about four times dia.) is a small spiral angle, preferably about 10°. Second choice are "Brass Type" drills, with a spiral angle of 25°. Such drills will work satisfactorily for depths up to about 4 times the dia., especially when provided with a flat ground along the cutting edge. This flat will reduce the tendency of the drill to hook into the work and to lift it when the point breaks through the under side. 40° spiral drills show this tendency to an even greater extent. They are satisfactory, however, when the work is firmly clamped. Fig. 13 shows a 10° spiral drill, and Fig. 14 a "Brass Type" drill with flat ground on.

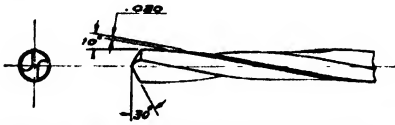


Fig. 13— $\frac{3}{8}$ in. dia. drill for short holes—recommended type.

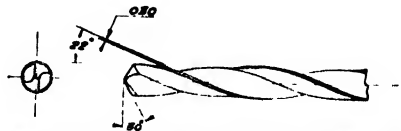


Fig. 14— $\frac{3}{8}$ in. dia. drill for short holes—permissible type. (Note flat ground along cutting edge.)

Speeds and Feeds in Drilling—Peripheral speeds of about 300 ft. per min. are considered standard practice for magnesium by many machine shops. The feeds should be considerably heavier than those used on other metals, for instance about 0.020-0.040 in. on $\frac{1}{4}$ in. holes.

Counter Boring—A recommended counter boring tool is shown in Fig. 15. An important feature is the narrow cylindrical land which is only about 0.015 in.

Tapping—A suitable tap design is illustrated in Fig. 16. The acute back angle of the land (3-4°) results in cutting rather than squeezing the metal when backing out of the tapped hole. The slightly greater springback of magnesium as compared with other metals makes this precaution advisable. The lands should be shorter than usual and cylindrical, that is, there should be no clearance on the land. This will reduce the possibility of chips getting jammed in the clearance space and building up on the land. Unlike drills, taps for magnesium are usually not made oversize. The resulting tight fit of the stud is desirable for satisfactory service. A thread-length of two to three times the diameter is recommended.

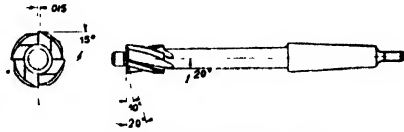


Fig. 15—Counterboring tool

No trouble is encountered with the "seizing" of threaded magnesium parts, when in contact with magnesium, aluminum or any other metal. Steel or brass inserts should be used in cases where the screw bolt or stud is frequently removed.

Grinding—Medium hard grinding wheels of melted clay bond with a grain size varying from 40 (medium coarse) to 80 (medium fine) are satisfactory for most purposes. For rough grinding (snagging), a grain size of about 20 is recommended. In grinding magnesium, a certain fire hazard is involved. The recommendations given below will practically eliminate this hazard and should therefore be carefully followed.

Wet Grinding—A liquid cooling agent, preferably crude oil, should be used whenever possible. The oil vapors developed during grinding should be exhausted. In those cases where exhausting is impracticable, a 3-4% soluble oil solution or a mixture of 10 gal. of water; 3½ pints of crude oil; and 3½ lb. of sodium carbonate should be used. In exceptional cases water may be employed. Any adhering traces of the solution should be removed from the magnesium parts soon after grinding.

Dry Grinding—In cases where the use of a liquid coolant is not practicable, the grinding may be done dry if provision is made for exhausting the grinding dust with sufficiently high suction speed (80-100 ft. per sec.). The grindings should either be precipitated by means of a water spray as soon as possible after leaving the grinding wheel or they may be sucked into an overflow water tank. A part of the grindings will flow into the sewer with the water while the rest settles down to the bottom of the tank and should be removed every two or three weeks. The exhaust pipe system should be equipped with safety valves to safeguard against explosion.

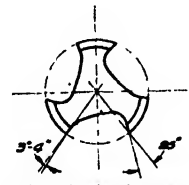


Fig. 16—Angles recommended for taps.

The following additional precautions are suggested:

- (1) Sparking of any kind is to be avoided in the vicinity of equipment on which magnesium is ground.
- (2) Iron or steel must not be ground on wheels used for magnesium nor in their vicinity. Grinding wheels for magnesium should be clearly marked as such.
- (3) An easily removable apron and hat should be worn by the operator. Rubber clothing is particularly recommended because of its smoothness. Anything apt to collect grinding dust on the clothing of the operator should be avoided, such as pockets or a rough clothing surface. Goggles should be used.
- (4) Grindings should not be allowed to accumulate on the clothing of the operator. They should frequently be brushed off or blown off with air.
- (5) The grindings should be frequently removed from the machines and placed in tightly covered iron cans in a location which is safe from sparking and fire. The magnesium content of grindings cannot economically be recovered and should be disposed of in water.
- (6) Before dressing the grinding wheel, the exhaust device should be shut off and all magnesium grinding dust blown off the machine and the wheel.

Polishing—In polishing, sandpaper of a suitable grade should be used. Emery paper will tend to cause sparking and is therefore not recommended. In order to maintain the bright shine of the polished surface, it should be slightly greased with vaseline or an equivalent grease, or painted with a recommended brand of clear lacquer. Polished surfaces not protected in this way will soon tarnish. For larger polishing operations, the same precautions as for grinding are recommended.

Sawing—Magnesium is readily cut by band or circular saws. Sharp blades are essential for satisfactory results. Lubricating with a tallow stick will facilitate the work.

The following is recommended for band saws:

	Thickness of Blade, in.	Width of Blade, in.	Teeth per inch
For smaller work.....	.030—.040	$\frac{1}{8}$ —1	8
For heavier work.....	.045—.050	$1\frac{1}{2}$ —2 $\frac{1}{2}$	5

The set of the teeth should be greater than standard so as to reduce friction. For circular saws, blades of about 10 in. dia. and .040 in. thickness with 5 to 7 teeth to the inch and a set of about .055 in. are satisfactory for cutting sections up to about 2 in. dia. Hack saws should have 14-18 teeth to the inch, every third tooth being a clearance tooth without set. A satisfactory size is .025-.030 in. thickness and $\frac{1}{2}$ in. width.

Filing—For hand work, single or double cut files may be used, although single cut files work better. Files with rasp cut produce too rough a surface. Depending on the smoothness desired, bastard, second cut or smooth files are used. For rotary files, medium coarse single cut files are found best. Too coarse a cut will result in chattering.

Lubricating and Cooling—Due to its great ease of machining and the small amount of frictional heat developed with proper tools, magnesium may be machined dry without difficulty. Arrangements for dry machining should be made wherever possible, with the following exceptions:

(1) *Smooth Finish*—A lubricant may be used in reaming and occasionally in other operations, when the smoothest possible finish is desired. However, a slight change of the tool nose will usually produce the same result without lubricant.

(2) *Distortion*—At times the cutting heat generated in the work cannot be quickly dissipated and the part will distort during or after machining. This condition may be due to the particular shape of the work which may hinder the free flowing away of the heat, or it may be caused by excessive generation of frictional heat as described under "Prevention of Distortion." In those cases where the cause for the slow dissipation of heat cannot be eliminated, distortion may be prevented by cooling both the work and the tool with compressed air, or where this is not considered practicable, with a liquid cooling agent.

(3) *Fire Hazard*—For grinding, a liquid cooling agent should be used to eliminate the fire hazard. The same precaution is often applied in machining magnesium parts with an insert of ferrous metal as sparking sometimes occurs when the tool strikes the insert. Too slow a dissipation of heat as described under (2) may also lead to ignition under certain conditions and calls for the use of air or liquid cooling.

Lubricants or coolants with the lowest percentage of water should be selected, such as kerosene or preferably mixtures of equal parts of kerosene and pure lard oil. Soluble oil solutions (mineral oils) may be used but should be avoided, due to their greater oxidizing effect on the turnings. Vegetable oils are not recommended.

Prevention of Distortion—Occasionally, a slight distortion of magnesium parts is observed during or after machining. This is infrequent and can generally be attributed to the following:

Frictional Heat—This will often result in distortion. Magnesium has a lower specific heat than aluminum and is therefore more liable to heat and warp under friction. Factors (all of which are avoidable) causing frictional heat are:

- (1) Dull tools.
- (2) Tools with cutting angles other than those recommended above.
- (3) Very fine feeds and cuts.
- (4) Insufficient chip space.
- (5) Slow speed. This is liable to cause jamming of chips, especially in combination with small feeds. Fast speeds increase the centrifugal force and throw out the chips, thus reducing the tendency of the chips to jam.

Inadequate Clamping or Chucking—Magnesium alloys have a lower elastic modulus than other alloys, which may, at times, lead to somewhat greater deformation under the cutting pressure if light sections of the work are not rigidly mounted.

Casting or Heat Treating Strains have seldom been found to cause distortion of magnesium castings during machining. Castings with a tendency to such strains can be given a normalizing heat treatment when found necessary. In exceptional cases, however, this treatment is insufficient, and the casting strains are only released by the roughing cut. In such cases, the castings should be allowed to rest for two or three days between the roughing and finishing cut. In addition, they may, if

necessary, be given another normalizing treatment consisting of heating to about 500°F. for two hours and cooling slowly.

Automatic Screw Machine Work—Speeds and Feeds—Magnesium alloy screw machine stock (3-7% aluminum recommended) may be machined at higher speeds and feeds than used for other metals. Due to speed limitations of the machine, however, the maximum economies offered in machining magnesium may not be obtainable in all cases. The possible increase of the feed over other metals will depend on the conditions but a feed of approximately 40% higher than used on brass may be considered an average figure. In general, better results are obtained with heavy feeds than with light ones.

Box Tool—Tool angles recommended for box tools are shown in Fig. 17. A tool ground in this way will produce a satisfactory finish. The angle shown as 10° is to

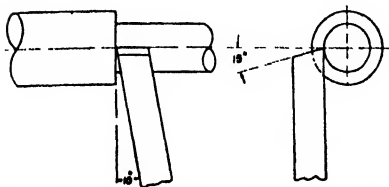


Fig. 17—Box tool for screw machine work

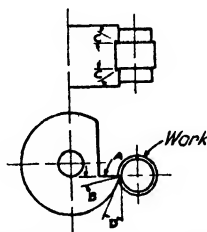


Fig. 18—Circular forming tool for screw machine work.

be considered an average and may vary within a relatively wide range depending on conditions (about 8 to 15°).

Circular Forming Tool—The circular form tool shown in Fig. 18 is one of the types most commonly used for automatic screw machine work. At "A" the tool is shown without top rake, which is satisfactory for magnesium. Frequently, it is necessary to grind the tool with a few degrees top rake as shown at "B" to correct a slight error in the steps of the tool. Top rake will produce satisfactory results but no rake is preferable as this will give better chip breakage. The side clearance indicated at "C" should not exceed one quarter degree. In most cases best results are obtained when the tool is without side clearance or with a slight negative rake.

The front clearance angle "D" is controlled by the design of machine and tool holder. A standard clearance angle has been determined for each type of machine and is considered satisfactory for all metals. This angle may vary slightly from one machine to another.

When using a side forming tool without support, the ratio of the width of tool to the smallest diameter on the work should not exceed 2:1 for magnesium.

Chips—With light feeds in machining magnesium, the chips form in coils or ribbons. When the feeds are increased, the chips break up and with relatively heavy feeds, they are well broken. The chips produced in machining magnesium do not increase in thickness as they pass across the tool. Their thickness is about equivalent to the advance of the tool, indicating that there is no adherence of the metal.

Cutting Oil—Contrary to ordinary magnesium machining practice, the use of a cutting oil is recommended for magnesium screw machine work. A grade of paraffin oil similar to that used for brass will be satisfactory for machining magnesium. The flash point of this oil should not be less than approximately 300°F.

Machine Shop Scrap—Care should be taken to keep the magnesium scrap free from contamination with other metals, floor sweepings and the like and as far as possible free from oil or moisture. They should be stored during accumulation in tightly covered metal containers. Grindings should be disposed of in water.

Fire Precautions—Ordinarily, the fire hazard in machining magnesium is slight and with a sound knowledge of the correct machining practice, ignition of the shavings may be easily avoided. In order to ignite magnesium, it is first necessary to reach the melting point of the metal. Partial melting begins, depending on the alloy, at temperatures between 800 and 1200°F. In roughing operations, it is very difficult to attain such temperatures, for the high heat conductivity of magnesium rapidly dissipates any frictional heat generated.

In finishing operations, however, where light shavings are necessarily produced, temperatures sufficiently high for ignition may, under certain circumstances, be reached. Factors which will tend to produce such temperatures in the chips or shavings are: (1) Very fine feeds or cuts. (2) Dull or chipped tools. (3) Tools with small clearances and small chip space. (4) High cutting speeds.

A combination of two or three of the above factors may lead to the ignition of the shaving. Sharp tools with ample clearance will greatly reduce the fire risk. Coarser feeds, deeper cuts and lower speeds will act in the same direction but in cases where fine feeds and cuts and highest speeds are essential to quality and economy of work, a liquid coolant should be used.

In turning, ignition may occur if the cutting is interrupted and the feed stopped while the work still revolves. In these cases, the tool should be backed away from the work. In machining magnesium parts with an insert of ferrous metal, sparking sometimes occurs when the tool strikes the insert. In such instances, the use of a lubricant has often been found advisable.

Under no circumstances should water or any other type of standard fire extinguisher, such as pressure or liquid type, be used for extinguishing a fire, as this will make the fire more violent instead of smothering it. Anything that shuts off the air from the burning chips will quickly and effectively smother the fire. The best way is to cover the burning chips with dry asbestos powder or dry cast iron turnings which should be easily accessible. It is recommended that a large container (about 6 cu. ft.) of dry cast iron turnings be placed at each machine. Dry or oil soaked sand is as effective as cast iron turnings but will soil the machine bed. Quick results are often obtained by smothering the fire with an iron plate or an asbestos mat or blanket. The smothering material should be gently applied in order to avoid scattering the fire. Air drafts will also tend to scatter the fire and should be avoided. A good precautionary measure is covering the floor around the machine with cast iron or steel plates.

In its initial stage, a spread of the fire may often be easily avoided by localizing the burning spot and scraping away the adjacent turnings. Care should in general be taken to avoid any accumulation of magnesium chips on, under or around the machine parts for the danger of the spread of the fire will be minimized if the amount of chips on the machine is small. Avoiding any accumulation of chips on the body or clothing of the operator is of particular importance. The chips should be removed at regular intervals and stored in tightly covered metal cans until they can be disposed of. Special fire precautions necessary in grinding are discussed under "Grinding."

Precautions During Machining—1. Do not allow chips or grindings to accumulate on machine or clothing. Store chips in covered metal cans. 2. Place a 6 cu. ft. container with cast iron turnings or dry sand at each machine. 3. Keep cutting tools sharp. Use tools with proper clearances. 4. Take heavy cuts. Back away tool from revolving work when not cutting. 5. Use lubricant when machining magnesium castings with steel or metal inserts or when taking light cuts at high speeds or when using dull or improperly designed tools. In all other cases machine dry. 6. Avoid any sparking. Avoid smoking. 7. Grind with lubricant or water or with dust exhausting equipment with precipitation of the grindings in water. 8. In grinding, a smooth and easily removable apron should be worn by the operator. 9. Do not grind steel or any other metal on wheels on which magnesium is ground. 10. Dispose of grindings under water.

Directions for Extinguishing Fires—1. Localize fire and scrape away adjacent turnings. 2. In initial stage, smother fire with iron plate, asbestos cloth or blanket. 3. Cover the oxidizing chips with one of the following materials: Cast iron turnings, dry sand, graphite, dry earth or asbestos powder. 4. Do not use water or any other type of standard fire extinguisher.

Riveting of Magnesium and Its Alloys

By H. Menking*

Rivet Alloy—Magnesium alloys can be riveted in a satisfactory manner with aluminum alloy rivets. For thin gages of sheet or for slightly stressed parts commercially pure aluminum (2S) rivets are recommended. For heavier gages and for stressed construction, a 5% magnesium (balance aluminum) rivet should be used. This alloy was developed in order to lessen corrosive attack of the magnesium sheet due to electrolytic action between sheet and rivet. Aluminum alloys with different magnesium content may also be used under less severe corrosive conditions.

Steel, copper, brass, bronze or duralumin rivets are not recommended because there is a possibility of electrolytic action in the presence of moisture and insufficient paint protection. Magnesium alloy rivets do not develop electrolytic action in contact with magnesium alloy sheet, but are not satisfactory due to their low shear strength and the necessity of driving them hot even in small sizes. Magnesium alloy rivets are therefore not supplied commercially.

Physical Properties—The 5% magnesium-aluminum alloy rivets are made from annealed wire and are supplied in the "as formed" condition. Typical physical properties of this alloy are as follows: Tensile strength, 41,000 psi.; yield strength, 18,000 psi.; elongation, 33%; Brinell hardness, 71; shear strength of cold driven rivet, 32,000 psi.; pressure required to drive $\frac{1}{8}$ in. buttonhead rivets (cold), 23 tons.

Design and Preparation of Riveted Joints—The rivets should not be placed too close to each other or to the edge of the sheet as this may lead to local over-stressing. A minimum distance of twice the rivet diameter is recommended between rivet and edge of sheet and three times the rivet diameter between rivets. The following rivet diameters are suggested for the lighter gage sheets.

Sheet Thickness, in.	Up to 0.040	0.040-0.060	0.060-0.100	0.080-0.120	0.100-0.140
Dia. of Rivet, in.	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$

The rivet holes should be drilled rather than punched, as punching tends to produce a rough and flaky surface in the hole. If punched, they should be finished with a drill to obtain a smooth surface. Rounding the edges of the hole will reduce edge stresses and fatigue failures. In driving the rivet, care should be taken to avoid damaging the sheet with the riveting hammer. Rivet shanks should fit holes snugly. For rivet dia. from $\frac{1}{8}$ - $\frac{1}{2}$ in. the clearance should be not more than $\frac{1}{32}$ in. and not less than $\frac{1}{64}$ in. Care should be taken to avoid loose joints. The rivet shank should not be too long in proportion to the rivet hole as otherwise high lateral stresses will be exerted on the sheet during driving, which will reduce the strength of the joint and may lead to fatigue cracks or to cracks of the sheet edge under the rivet head during driving. In driving the rivets in the shop, the use of cone point head tools is recommended. Cone point heads, as compared with other types of heads, require less driving pressure and reduce the tendency of the sheet and the rivet head to crack. The pressure required to drive magnesium-aluminum rivets is slightly lower than that required for duralumin (17S) rivets. No heat treatment of any kind is required for the magnesium-aluminum alloy.

The magnesium-aluminum rivets (AM55S) of $\frac{1}{8}$ in. dia. and over are usually driven hot. In this case, the rivets should be preheated in an oven to about 630-670°F.

Corrosion Prevention—In those cases where corrosive conditions are apt to be encountered, and where the rivet is driven cold, it should be dipped into a suitable bitumastic paint prior to placing in the rivet hole in order to prevent electrolytic corrosion. The excess paint will be squeezed out under the rivet head and will form an insulating layer. Although the magnesium-aluminum and commercially pure aluminum alloy rivets have only a slight tendency toward electrolytic action in contact with magnesium sheet, the above procedure will serve as an additional safeguard to prevent corrosion under conditions of ordinary exposure, and should always be used for applications in the presence of salt air or salt spray. The excess of semisolid paint or sealing compound squeezed out from under the rivet head should be removed before painting the riveted structure to prevent its bleeding through the paint. The contacting surfaces of the riveted magnesium sheet or extruded shape should be painted before assembly.

*American Magnesium Corp., Cleveland.

In those cases where the magnesium-aluminum or 2S alloy rivets are not available and duralumin rivets must be used, the above precautions for protection should be followed even more rigidly because of the greater tendency to electrolytic action. In such cases, in addition to the above measures, gaskets or washers are recommended between the rivet head and the magnesium surface to insure the necessary insulation. Suitable gasket materials are: Bakelite; fiber; gasket paper; leather free from chromium salts; hard rubber; heavy paper, treated with shellac, bitumastic paint, a primer in accordance with Navy specification P-27; or Bakelite varnish.

If fiber or commercial gasket paper is used, the particular brand used should be analyzed to make sure that it does not contain chlorides or other salts.

Protection of Magnesium Against Corrosion

By John A. Gann*

General—Magnesium alloys are quite resistant to corrosion under ordinary urban and rural exposure. Under such conditions, the metal gradually dulls and darkens but suffers no loss in mechanical properties. Corrosion may become more pronounced in heavy industrial areas and particularly along the sea coast. This results in a roughening of the surface and even pitting under extreme conditions. The alloys are free from intercrystalline corrosion so that changes in properties due to corrosion can be estimated by the amount of surface attack.

The corrosion resistance of magnesium alloys to many chemicals has been determined in laboratory tests and under actual operating conditions. Inasmuch as the corrosion resistance of any metal is affected not only by the medium to which it is exposed but also by the operating conditions, service tests should always be made before using magnesium alloys for any special applications. Table I indicates the corrosion characteristics of magnesium alloys in contact with a variety of materials.

Table I
Corrosion Characteristics of Magnesium Alloys

Chemical	Concentration ¹	Recommendation ²
Acetic acid	Any	N
Alcohol, butyl	100%	R
Alcohol, ethyl	100%	W
Alcohol, methyl	100%	N
Ammonium salts	3%	N
Ammonium hydroxide	Sp. gr 0.88	R
Ammonia, gas or liquid	100%	R
Aniline	100%	W
Beer	100%	N
Benzene	100%	R
Calcium salts	3%	N
Carbolic acid	See Phenol	
Carbon bisulphide	100%	R
Carbon tetrachloride	100%	R
Carbonated waters	Any	N
Castor oil	100%	R
Chromates, most	Any	R
Chlorides, all	Any	N
Chromic acid, pure	Any	R
Formaldehyde	50%	W
Fruit juices	Any	N
Gasoline, regular	100%	W
Gasoline, ethyl	100%	W
Hydrochloric acid	Any	N
Hydrofluoric acid	10 to 50%	R
Hydrofluoric acid	1 to 10%	N
Hydrogen peroxide	3 to 30%	N
Ink, iron	100%	N
Ink, dye	100%	R
Kerosene	100%	R
Linseed oil	100%	R
Mercury	100%	N
Milk	100%	N
Oil, chloride free	100%	R
Phenol (carbolic acid)	100%	R
Salt (sodium chloride)	Any	N
Sea water	100%	N
Sodium carbonate	3%	R
Sodium fluoride	3%	R
Sodium hydroxide, pure	3 to 50%	R
Sodium salts, most	3%	N
Steam, 100°C.; 212°F.	100%	N
Steam, 120°C.; 248°F.	106%	N

¹Concentrations other than 100% refer to water solutions of the chemical.

²Recommendations are based on the behavior of unprotected metal. In a few cases protective coatings permit the use of magnesium alloys with chemicals that normally corrode them.

R = recommended for use. N = not recommended for use. W = may be satisfactory, but trial under operating conditions is warranted.

Magnesium alloy parts are generally given protective paint coatings because it is difficult to control the location and conditions under which they will be used

*The Dow Chemical Co., Midland, Mich.

Many jobs are painted for decorative purposes. In order to secure maximum protection, it is necessary to follow certain established procedures, discussed below.

Cleaning—Prior to the application of a chemical treatment to magnesium alloys, it is necessary to have the surface free from dust, dirt, oil, and grease. Loosely adherent material should be brushed off. Oxide films and adherent dirt should be removed mechanically, by sand blasting, wire brushing, or grinding; or chemically, by pickling in a 1-10% solution of sulphuric acid. After the acid pickling, the parts should be given a wash in cold running water followed by a hot water (140-180°F.) rinse to facilitate drying.

Oil and grease are removed by washing with an organic solvent such as carbon tetrachloride, gasoline, or naphtha; or by treatment in hot alkaline cleaners. Parts cleaned with organic solvents should receive a final rinse in clean unused solvent. The mild alkaline cleaners developed for aluminum can be used, but faster and more efficient cleaning will be obtained through the use of the stronger alkaline cleaners, as used on steel, or an inexpensive mixture made in accordance with the following formula:

Sodium Carbonate (Soda Ash).....	3 oz.
Sodium Hydroxide (Caustic Soda).....	2 oz.
Soap	1 oz.
Water, to make.....	1 gal.

Magnesium alloys are not attacked by such cleaners, which should be used at boiling temperature. Parts so treated should be given a wash in cold running water, followed by a hot water rinse to facilitate drying.

Chemical Treatment—Magnesium alloy surfaces must be given a chemical treatment prior to painting in order to insure satisfactory results. The application of ordinary paint coats to bare magnesium, regardless of how well it may have been cleaned, will result in unsatisfactory adhesion to the metal. No paint is entirely impervious to moisture; and sooner or later, depending on the conditions of exposure, the paint will begin to lift from untreated metal. This may take place without apparent attack on the underlying metal.

Chrome Pickle Treatment—The chemical treatment generally used is known as the "chrome pickle" or "bichromate coating." It is well bonded to the metal, has a satisfactory mechanical tooth for subsequent paint coatings, and has definite corrosion inhibitive characteristics. This treatment is a simple dip operation requiring ½-2 min., according to the freshness of the bath and cleanliness of the article. The recommended bath has the following composition and is operated at room temperature:

Sodium dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$).....	1.5 lb.
Nitric acid (HNO_3 , sp. gr. 1.4).....	1.5 pint
Water, to make.....	1 gal.

Containers for this bath should be made of pure aluminum, glass, or earthenware. After the dip, the parts should be held above the tank for about 5 sec. This serves a double purpose; to allow the adhering solution to drain off, and to produce a better colored and more effective coating. The parts are now washed in cold running water, followed by a hot water rinse which completes the washing and facilitates drying.

The chrome pickle treatment produces a visible color with a matte to bright finish on the article. The color and luster vary with the composition or age of the solution and also with the composition and type of heat treatment of the alloy. Matte, gray to yellow-red, iridescent coatings are best paint bases and are readily obtained in fresh solutions. Bright brassy coatings are to be avoided. They are produced in solutions which contain too much acid, or in solutions which have been revived too many times.

The bath may be operated until the nitric acid content is depleted to 1.0 pint per gal. at which stage the sodium dichromate concentration will be about 1.3 lb. per gal. The solution should then be revived to contain 1.3 to 1.4 pints of nitric acid and 1.5 lb. of sodium dichromate per gal. This reviving operation may be performed 7 or 8 times, whereupon byproducts of the process will have built up in the solution impairing the efficiency to such an extent that the bath should be discarded. A rough control of the bath composition may be conducted on the basis of color of coating, etch produced, and degree of action observed. Exhaustion of the

solution is indicated by the paleness of color and slowness of action on the metal. This paleness in color should not be confused with that caused by insufficient exposure of air between removal from the bath and the wash in water. Nitric acid and sodium dichromate should be added until a matte or semimatte (not bright) coating is produced, remembering that the nitric acid content diminishes more rapidly than the sodium dichromate content.

Articles too large to be immersed should be well brushed with a generous amount of the solution (preferably freshly made), well washed with a brush and water, rinsed, and dried. The coating thus formed is less uniform in color than that produced by the dip process but is equally good as a paint base if sufficient solution is used. If die castings are to be given the chrome pickle treatment, the solution should be heated to 150°F. The time of treatment should be limited to approximately 5 seconds as a longer time results in the formation of a loose powdery deposit on the surface of the casting.

The chrome pickle treatment, as described above, is given in Specification M-303, part 1, Navy Department, Bureau of Aeronautics, and in United States Army Specification No. 98-20010.

Magnesium castings and wrought shapes are normally chrome pickled or bichromated prior to shipment. If this chemical finish is subsequently damaged or removed during forming or machining operations, the parts should be retreated prior to painting. Since the normal treatment removes 0.001-0.002 in. of metal, machined surfaces that must be held to accurate dimensions should be given a shorter time chrome pickle treatment or, as an alternative, the modified alkaline dichromate treatment described below.

Modified Alkaline Dichromate Treatment—This treatment is not intended to replace the chrome pickle treatment, but is recommended as an alternative for those cases in which dimensional changes, as on machined surfaces, are to be kept at a minimum. Parts given the treatment show no dimensional loss. Properly applied the alkaline dichromate treatment provides the magnesium alloy article with a black decorative finish.

Immediately prior to treatment, the parts must be very thoroughly cleaned in accordance with previous instructions, preferably with an alkaline cleaner or by boiling for five minutes in a solution of 2% sodium hydroxide followed by a hot water rinse. Next immerse parts 5 min. in a water solution containing 15 to 20% by weight of hydrofluoric acid (HF) at room temperature. Wash in cold running water and then immerse parts 45 min. in a boiling solution containing:

Ammonium sulphate, $(\text{NH}_4)_2\text{SO}_4$	4 oz.
Sodium dichromate, $\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$	4 oz.
Ammonia (sp. gr. 0.880).....	$\frac{7}{8}$ fluid oz.
Water to make.....	1 gal.

The treated parts should be washed immediately in cold running water. As the final step, boil parts 5 min. in a water solution containing 1% by weight of arsenous oxide (As_2O_3). Rinse parts thoroughly in cold running water followed by a dip in hot water to facilitate drying.

In large scale operation the sulphate-dichromate solution may be easily controlled and maintained at proper concentration. The pH value should be held between 5.6 and 6.2 by additions of chromic acid and concentrated sulphuric acid in equal proportions by weight. Aluminum or steel tanks can be used for the solution which can be heated externally with gas or internally with steam coils. A loosely fitted lid can be used to minimize loss by evaporation.

The alkaline dichromate treatment, as described above, is given in Specification M-303, part 3, Navy Department, Bureau of Aeronautics

Dichromate Boil—This treatment is simpler to apply but is just as effective as the modified alkaline dichromate. It is not, however, covered by government specification at this writing.

Clean parts and dip in hydrofluoric acid the same as in the modified alkaline dichromate treatment. Rinse in cold running water and then immerse parts 45 min. in a water solution containing 10% by weight of sodium dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$). Wash in cold running water and then dip in hot water to facilitate drying. Control is accomplished by keeping the bath at a pH of 4.2 by additions of chromic acid.

Painting—The successful painting of magnesium offers no unusual difficulties today where approved materials are used and good painting practice is observed. So far as the problem of protection is concerned, the service conditions fall into

three general classes: 1. Interior, such as in the home, office, or factory not employing corrosive chemicals; 2. Exterior, such as inland North American atmospheres; and 3. Seaboard atmospheres containing sea salts or spray, or tropical areas of high humidity.

Primers—Before priming, any grease, oil, or dust must be removed from the chrome pickled surface, preferably by a thorough solvent wipe. Under no circumstances should sanding, phosphate cleaner, or any other treatment designed to roughen the surface be used over the chrome pickle.

Care in the selection of the primer cannot be overstressed, especially in regard to its adhesion and corrosion inhibitive characteristics. Natural adhesion is the most important property for a primer to be used under average indoor and exterior conditions. Zinc chromate primers possess distinct inhibitive properties with fair adhesion and hence should be used where corrosion conditions are severe, such as exposure near salt water or to continuous moist air. In cases where it is difficult to predict the service conditions under which a piece of equipment will be used, it is generally best to employ a chromate primer meeting Navy Specification P-27 or Army Specification 14080.

Surfacers—A sealing or surfacer coat should be used over the primer coat and prior to the application of the finish coats where smoothness is of importance. Such a coat improves the adhesion and wear resistance of the paint job. For conditions of severe exposure, however, an additional finish coat has more protective value than a coat of surfacer.

Finishes—Almost any good quality oil paint can be used over a recommended primer on indoor exposure where wear resistance is not required. Full synthetic and oil-base synthetic enamels, or high grade spar varnish pigmented with aluminum paste, have proved satisfactory for general exterior work. Experience has demonstrated the economy of an additional finish coat, since the added protection is well worth the expense, especially on parts to be used on Naval aircraft. Lacquer type coatings should be used judiciously, since they appear to lack the necessary expansion characteristics. They may be useful, however, for certain interior applications. Clear coatings have only a limited application on magnesium. They are sometimes desirable for indoor service in order to preserve the natural metallic luster or to protect the various colored finishes.

Baked Finishes—The excellent adhesion and imperviousness possessed by the "baking type" materials make them well suited for use on magnesium. Schedules requiring baking temperatures up to 400°F. can be used on as-cast, aged, or wrought parts, while a maximum temperature of approximately 225°F. should be used on solution heat treated castings in order to avoid aging or precipitation heat treatment. Baked finishes are recommended for die castings, small sand castings, and other parts of convenient size, since the adhesion thus obtained is better than with air dried materials. Improved service performance can likewise be obtained by forced drying or baking of most air drying primers and finish coats based on synthetic resins.

Assembly Protection

Inclosed Type Structures—Protection should likewise be given prior to assembly, to all castings, parts, and surfaces that are concealed or inaccessible in the completed structure. This applies to the interior of castings such as aircraft wheels, which are not tightly sealed from external atmospheric conditions; also to castings which may be completely inside more or less inclosed locations, for example, aircraft control brackets mounted within wing structures.

Metal-to-Metal and Metal-to-Wood Contacts—Where magnesium is assembled in contact with magnesium, a different metal, or wood, there is a possibility of corrosion occurring from moisture condensation, galvanic action, or attack by acids or salts which may be leached from the wood. Iron and wood are particularly bad; the former on account of the galvanic action between it and magnesium, and the latter on account of its porous nature and tendency to retain moisture. Such trouble may be avoided by the use of asphalt paint or similar sealing materials. Rivets, bolts, screws, or washers should be coated with asphalt type paint just prior to use. Special conditions requiring a solid insulating material may employ Bakelite, sheet rubber, or cork gasket material.

Cleaning Assembled Structures—Excess asphaltic and bituminous sealing compounds that have been squeezed out between joined surfaces and around rivet or

Paint Schedule for Magnesium Alloys¹

Service Condition	Surface Preparation	Primer ²	Finish ³
Interior	Remove dirt and grease. Chrome pickle, Navy Spec. PT-3	One coat of zinc chromate primer meeting Navy Spec. P-27, or one coat of a metal primer possessing max. adhesion as shown by test.	One or more coats of good quality oil paint or enamel. Lacquers must be used judiciously because of their low expansion and brittleness.
Exterior	Remove dirt and grease. Chrome pickle, Navy Spec. PT-3	One coat of zinc chromate primer meeting Navy Spec. P-27, or one coat of a metal primer possessing max. adhesion as shown by test.	Two or more coats of enamel characterized by high durability such as the synthetic resin enamels of the phenolic or glycerol phthalate type meeting Navy Spec. M-67 and E-5 respectively, or two or more coats of the same type varnish meeting Navy Spec. V-10 and V-11 pigmented with 1½-2 lb. of aluminum paste per gal.
Seaboard	Remove dirt and grease. Chrome pickle, Navy Spec. PT-3	One or two coats of zinc chromate primer meeting Navy Spec. P-23 or, preferably, Navy Spec. P-27.	Three or more coats of synthetic resin enamel of phenolic type meeting Navy Spec. M-67 or three coats of synthetic resin varnish of phenolic type meeting Navy Spec. V-10 pigmented with 1½-2 lb. of aluminum paste per gal.

¹Baked finishes are recommended where adaptable (see text).²Synthetic resin primers and finishes are generally improved by a forced drying of each coat for 1 hr. at 225-250°F. A surfacer or filler coat may be used over the primer coat when smoothness and appearance are of importance.³A surfacer or filler coat may be used over the primer coat when smoothness and appearance are of importance.

bolt heads, must be removed prior to painting, since they are likely to bleed through subsequent paint coatings. This is readily accomplished through the use of a commercial retarder thinner or with similar and less expensive materials, such as butyl alcohol, butyl acetate, or naphtha. A final naphtha or similar solvent wipe should be given the completed assembly immediately prior to painting.

The basic principle in the protection of magnesium alloy parts is to keep the metal as dry as possible through proper design which eliminates moisture-retaining pockets and joints, through the use of sealing paints or compounds, and through the use of impervious paints applied over corrosion inhibitive chemical coatings. When this has been done, no trouble should be experienced in securing adequate protection of the metal.

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The Nickel Industry

By A. J. Wadhams*

Nickel was used by ancient man in swords and implements fashioned from nickel-bearing meteorites and in coins made from paktong, a nickel-copper alloy derived from China. It was extracted as an element in 1751 by Axel F. Cronstedt and named nickel from the ore "kupfer-nickel," so-called by superstitious miners who believed the ore bedeviled. The modern nickel industry dates from the opening of the New Caledonia mines in 1875 and those of Sudbury, Ontario, in 1886.

Occurrence—Commercial nickel ores fall into three major classes: (1) Sulphide ores, represented chiefly by the pyrrhotite-pentlandite-chalcocopyrite ores of Canada and Norway. Pentlandite, a complex nickel-iron sulphide, is the nickel carrier. Small quantities of ores of this type have been mined in Connecticut, Pennsylvania, California, Missouri, and in Sweden, Finland, Italy, China, Tasmania, South Africa, and Great Britain. (2) Oxidized ores of the garnierite (silicate) type, occurring in New Caledonia, and in small quantities on the border of North Carolina and Tennessee. Similar ores occur in Borneo, Madagascar, Brazil, Spain, Greece, Russia, the West Indies, and Oregon. (3) Arsenical ores, found in Ontario, Colorado, New Mexico, Saxony, Bohemia, France, and eastern India. Small percentages of nickel are also present in many of the copper ores, in manganese ores of the early class known as wad, and in nickeliferous ores such as those of Cuba.

Smelting and Refining—In the Orford process, the ore is ground fine, classified, roasted in Nichols-Herreschoff roasters, and smelted in reverberatory furnaces to remove a large part of the sulphur. The molten matte is charged into converters with silicious flux to produce a fluid slag which carries off the iron. The resultant nickel-copper Bessemer matte is smelted in a blast furnace with an alkaline sulphide flux and subsequently cast into large pots. The product solidifies in two layers. The top layer contains copper sulphide; the bottom layer contains nickel sulphide. Re-smelting with nitre cake and excess coke progressively purifies the product. The copper is blown to blister in basic lined converters and refined electrolytically. The nickel sulphide bottoms are crushed, leached and sintered, melted in reverberatory furnaces and cast into anodes. By electrolytic refining in a continuously purified nickel sulphate electrolyte, cathode nickel having a purity of 99.95% (plus cobalt) is obtained. The cobalt content range is 0.30-0.50%. Impurities may be copper, iron, carbon, sulphur, and silicon.

In the Mond process, crushed nickel sulphide bottoms are calcined to drive off sulphur, reduced to metal, and then treated with carbon monoxide gas, which forms a volatile nickel compound (nickel carbonyl) at 60°C. The nickel-laden gas is passed over pure nickel pellets at a higher temperature (about 180°C.). Metallic nickel is deposited on the pellets and the regenerated carbon monoxide is returned for use again as a nickel carrier.

The New Caledonian silicate ore is smelted to matte. Sulphur is supplied by adding gypsum or any alkaline sulphide to the furnace. The matte is blown to a high grade in Bessemer converters and the iron eliminated in the slag. After roasting to drive off the sulphur, the oxide is made into a plastic with reducing materials and produced in the shape of cubes or rondelles.

Products—Nickel is marketed in various forms as follows: (1) Nickel pellets produced by decomposition of nickel carbonyl gas without fusion; (2) electrolytic cathode sheets cut into various sizes; (3) blocks or shot obtained by remelting electrolytic nickel cast into pig molds or poured into water without deoxidation; (4) malleable nickel produced by pouring into ingot molds after deoxidation; (5) nickel cubes or rondelles reduced from the oxide without fusion; (6) nickel salts; (7) nickel oxide; (8) nickel powder.

Uses—Nickel is used in the food processing, radio, and chemical industries, in coinage, in the Edison storage battery, and as a catalyst in the hydrogenation of unsaturated organic compounds. Nickel plating is extensively employed and regularly forms a base layer for chromium plating. Heavy nickel plating has been developed for building up the worn parts of machinery, and a hard plate (up to 400 Brinell) is utilized for applications requiring unusual resistance to abrasive wear. Nickel clad steel has been developed for the construction of heavy tanks and kettles.

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Nickel finds its most extensive application as an alloying element in ferrous and nonferrous alloys. Table I serves to indicate the percentage distribution of nickel in the various metal markets and Fig. 1 shows the world production.

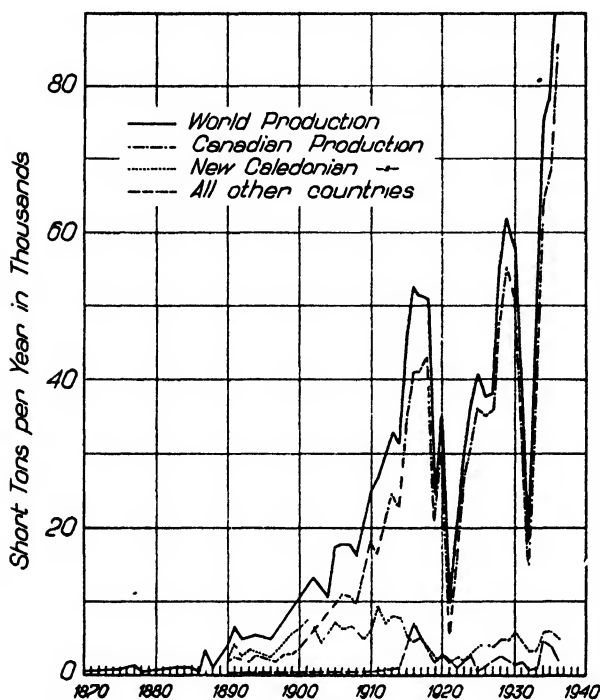


Fig. 1—World nickel production, 1870-1936.

60% nickel and 15% chromium is used in electrical resistance heating elements. An 80% nickel, 14% chromium, 6% iron alloy has good strength, toughness, and corrosion and oxidation resistance. It finds application in chemical and food processing equipment.

Table I
Approximate World Nickel Consumption

Construction steels, stainless steels and other corrosion and heat resisting steels, and steel castings	80%
Nickel cast iron	3%
Nickel-iron alloys	1%
Nickel-copper alloys and nickel silvers	14%
Nickel brass, bronze, and aluminum alloy castings	2%
Heat resistant and electrical resistance alloys	3%
Malleable nickel, nickel clad	9%
Electrodeposition	6%
Nickel salts, ceramic materials, storage battery materials and catalysts	1%
Miscellaneous and unclassified	1%

A variety of nickel-iron alloys have special thermal, magnetic, electrical, and elastic properties. Invar, containing 36% nickel and possessing a coefficient of thermal expansion of approximately zero, is one of this series. A 20% nickel alloy containing aluminum and cobalt has been developed for permanent magnets.

Monel is a copper-nickel alloy containing 67% nickel, 30% copper, the balance mostly iron and manganese. It is obtained by roasting copper-nickel converter matte and reducing the resulting oxide to metal with charcoal. This alloy is primarily a corrosion resistant alloy for handling acids, alkalies, brines, waters, and food products, and is resistant to exposure in dry and moist atmospheres.

Nickel is one of the chief alloying elements of the alloy steel industry. Its most outstanding characteristic is its ability to impart to steel increased hardness, strength, and toughness without sacrifice of ductility. Nickel steels find extensive application in the transportation field, in the oil and power industries, and in machine tool, agricultural and general machinery construction. In cast iron, nickel possesses the added advantage of refining the grain, promoting homogeneity and density, and reducing the tendency to chill. Special nickel cast irons have been developed for abrasion resistance and for heat and corrosion resistant applications.

Nickel-chromium steels carrying high percentages of the alloying elements form a series of corrosion and heat resistant alloys. The most popular of these, 18-8, contains 18% chromium and 8-10% nickel. A ferrous alloy containing

Nickel-copper alloys containing 20-30% nickel are used for condenser tubes handling sea water. A 25% nickel alloy is used for the United States' five cent coin. An alloy containing 45-55% nickel is marketed under a variety of trade names for pyrometer and electrical resistance wire.

The effect of nickel as a decolorizer is utilized in the nickel silvers, widely employed for architectural trim and plumbing fixtures, and finds application in the production of white gold. Nickel up to 2% is also used in several of the aluminum alloys including sand cast, permanent mold, die cast, and wrought products.

The approximate compositions and melting points of the nickel alloys used for melting in the nonferrous industry are as follows:

	Electrolytic nickel cathode	Shot and ingot from electrolytic nickel	Nickel- copper shot	Copper- nickel shot	High nickel- copper shot and blocks
Nickel (Plus Cobalt)	99.95%	99.60%	66.65%	50.07%	67.00%
Iron	0.01-0.04%	0.07%	0.66%	0.10%	1.75%
Copper	0.01-0.03%	0.026%	32.29%	49.57%	29.00%
Carbon	trace	0.11%	0.19%	0.06%	0.20%
Silicon	trace	0.11%	0.055%	0.04%	1.25%
Sulphur	trace	0.01%	0.017%	0.02%	0.01%
Manganese	0.13%	0.06%	0.75%
Melt Point, °F.	2650	2600	2400	2250	2460

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Constitution of Nickel-Aluminum Alloys

By R. H. Schaefer*

For many years the only published diagram of this system was that of Gwyer¹ who was mainly interested in aluminum-rich alloys. In 1934 Fink and Willey² examined alloys containing up to 18% nickel and made a careful determination of

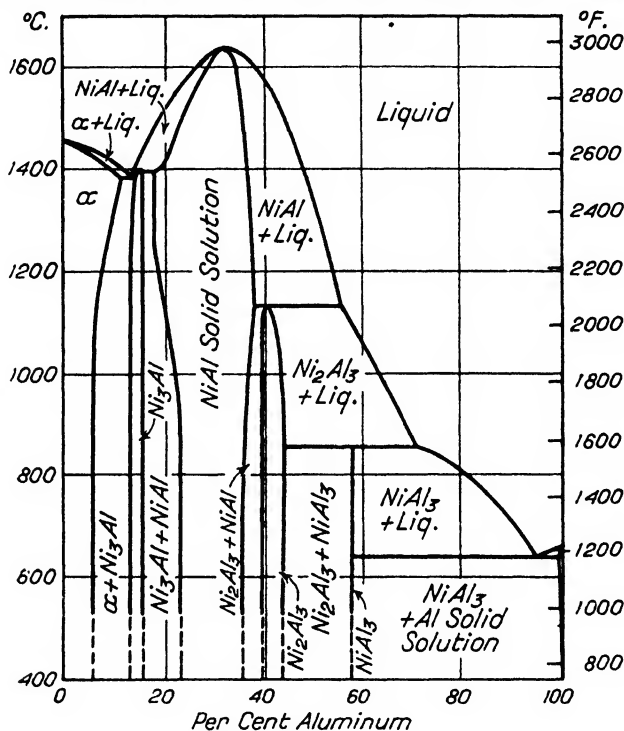


Fig. 1—Nickel-aluminum constitution diagram.

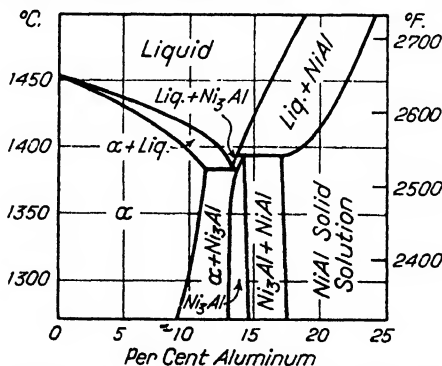


Fig. 2—Nickel end of the nickel-aluminum constitution diagram.

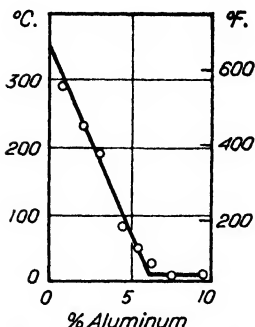
the eutectic temperature and composition, and the solid solubility of nickel in aluminum at various temperatures. These data are reported on p. 1230 of this Handbook. However, except for Bradley and Taylor's X-ray data which relates mainly to the phase limits at room temperature and to the atomic structure of the

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various phases, it was not until 1937 that the whole system was re-investigated by Alexander and Vaughan,⁴ whose careful work included thermal analysis, microscopical examination and hardness measurements. Their diagram, with the exception of a slight modification of the NiAl boundary on the nickel side is shown in Fig. 1 and 2.

Both Bradley and Taylor, and Alexander and Vaughan agree that below 700°C. nickel forms a face-centered cubic terminal solid solution up to about 5% aluminum, that a two phase region exists between 5-13.3% aluminum, and that a face-centered cubic intermediate phase or Ni₃Al forms between 13.3-15.5% aluminum. However, the former authors, on the basis of X-ray data secured on quenched powder samples, concluded that the two face-centered phases showed increased mutual solubility at higher temperatures so that at 1100°C. the duplex field between 5-13.3% aluminum disappeared as opposed to the interpretation given in Fig. 1 and 2. Because of the possibility of losing aluminum through oxidation of the heated powder samples which would move the composition of the alloys towards the alpha field, and what appears to the author to be inconsistencies in the data of Bradley and Taylor when evaluated on the basis of their proposed equilibria, the interpretation of Alexander and Vaughan has been used. The Ni₃Al phase is reported to have a superlattice with aluminum atoms occupying the cube corners and nickel atoms the centers of the cube faces.

Fig. 3—Effect of aluminum on the Curie temperature of nickel.



contains 31.5% aluminum. The nickel-rich limit of this phase from about 1100°C. down is based upon the room temperature value of 23.5% aluminum reported by Bradley and Taylor since the alloys prepared by Alexander and Vaughan were quite widely spaced in this region.

At a somewhat higher aluminum content the intermediate Ni₃Al, which was originally thought by Gwyer to be NiAl, is formed by a peritectic reaction between NiAl and the liquid at 1133°C. This phase has a pseudo cubic structure with aluminum atoms lying very near to the cube corners and nickel atoms at the centers of two-thirds of the cubes. At 854°C. and 58% aluminum the intermediate phase NiAl, is formed by a peritectic reaction between Ni₃Al and the liquid. The intermediate phase NiAl, is the only one in the system which does not tolerate either excess aluminum or nickel. The structure of this phase appears to be orthorhombic with a unit cell consisting of four nickel atoms and twelve aluminum atoms.

The effect of aluminum on the Curie temperature of nickel is shown in Fig. 3 which is reproduced from the work of Marian.⁵ The abrupt knee in the curve at about 6% aluminum results when the limit of the alpha solution field is reached and may occur at a slightly lower aluminum content than indicated.

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Constitution of Nickel-Beryllium Alloys

By D. E. Ackerman*

Although the age hardening properties of the nickel-beryllium alloys have been studied by a number of investigators, our knowledge of the theoretical aspects of the system is based, for the most part, upon the work of Masing and Dahl¹ who confined their attention to the nickel-rich end of the system. More recently Gerlach² has checked the lower temperature course of Masing and Dahl's alpha field boundary and has extended the boundary to lower temperatures. The two sets of data are in excellent agreement in the ranges in which they overlap.

The present constitution diagram is reproduced in Fig. 1. Small beryllium additions rapidly depress the liquidus temperature from 1455°C. for pure nickel to 1157°C. at 5.1% beryllium; at the latter point an eutectic of the saturated solid solution,

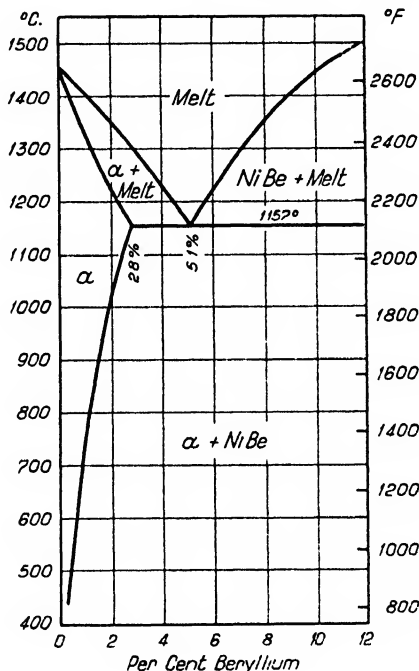


Fig. 1—Nickel-beryllium constitution diagram.

containing 2.8% beryllium, and the compound NiBe is formed. The liquidus temperature again rises as the beryllium content is increased above 5.1%; presumably, this increase continues until the melting point or decomposition temperature of the compound NiBe is reached.

The solubility of beryllium in nickel decreases markedly with decrease in temperature, ranging from 2.8% beryllium at the eutectic temperature (1157°C.) to 0.3% beryllium at 450°C.

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Constitution of Nickel-Carbon Alloys

By R. H. Schaefer* and T. E. Kihlgren*

Our knowledge of this system arises principally from the work of O. Ruff in collaboration with various other investigators^{1, 2, 3, 4} and the later studies of T. Kasé.⁵ In Fig. 1, the liquidus curves and the eutectic horizontal are based on the combined data of Kasé and those of Ruff and his collaborators. The alpha solid solubility curve between 1250 and 995°C. was obtained from data secured at the International Nickel Co. Research Laboratory. The magnetic transformation curve is based on Kasé's data.

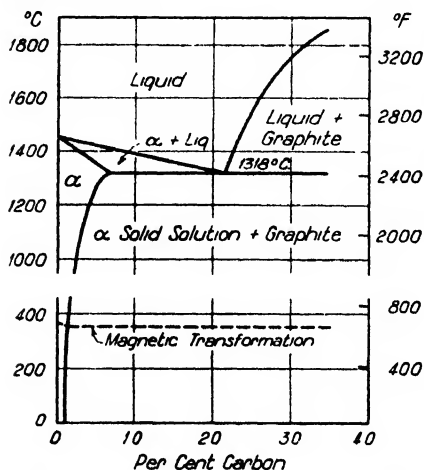


Fig. 1—Nickel-carbon constitution diagram.

graphitic and total carbon. The carbon in solid solution was obtained by difference. The alpha phase boundary of Fig. 1 is based on these data which are shown below, the deviation between the two sets of determinations varying from 0 to 0.03% C.:

Determination of Carbon Solid Solubility

Temperature, °C.	% Carbon in Solution	
	Sample No. 1*	Sample No. 2†
993	26	23
1135	35	35
1256	47	
1264		.47
1307	.58	...

*Contains 0.076% Si, about 0.65% total carbon (after homogenization)

†Contains 0.10% Si, about 1.30% total carbon (after homogenization)

The solid solubility at the eutectic temperature is apparently of the order of 0.65% carbon. The curve has been extrapolated from 995°C. to room temperatures, to agree with the data reported by the Bureau of Standards.

The liquidus temperature reaches a minimum at the eutectic temperature 1318°C. at 2.22% carbon and as the eutectic concentration is exceeded, the liquidus temperature is raised. Ruff and Kasé are in good agreement on the liquidus of alloys containing up to about 2.9% carbon, beyond which Kasé presents no data. The studies of Ruff and Martin⁶ extended to higher carbon contents and indicated that the liquidus increases with the carbon content to about 6.42% carbon at which there is a sharp break in the curve. This carbon content corresponds to the compound Ni_3C which Ruff and Martin⁶ consider to exist between 1500 and 2500°C., but which is readily decomposed. Their data are indicated in the tabulation:

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Temperature, °C.	Total carbon dissolved, %
1560	2.50
1640	2.69
1640	2.73
1744	2.98
1842	3.38
1950	4.04
1956	3.97
2050	5.30
2100	6.42
2200	6.38
2200	6.30
2300	6.32
2400	6.31
2500	6.30

Ruff and Gersten⁵ determined the heat of formation of Ni_3C to be -394 ± 10 calories and concluded that this compound, being highly endothermic, is extremely unstable. Nickel carbide has not been observed as a constituent in commercial grades of nickel, confirming the view that if a carbide of nickel does exist, it is indeed unstable.

The data on the magnetic transformation of nickel-carbon alloys are not very satisfactory, Kasé's magnetic analysis having been made on chill cast unhomogenized specimens. Repeat runs were made on two alloys and these showed a gradual increase in the Curie temperature due presumably to a closer approach to equilibrium. The data indicate that the magnetic transformation of nickel is depressed by carbon to about 350°C ., at the limit of solid solubility of carbon in nickel, and is apparently unaffected by further increases in carbon content.

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Constitution of Nickel-Chromium Alloys

By E. M. Wise* and R. H. Schaefer**

The first attempt to establish the constitution of this alloy system was made by Voss¹ in 1908 who found a minimum in the melting curve at 42% nickel and at this composition found an eutectic-like structure which he ignored in his published diagram. The system was generally considered to be of the solid solution type, but with present knowledge that the structure of nickel is face-centered cubic and chromium body-centered, a continuous series of solid solutions would not be expected and microscopic^{2, 3} and X-ray^{4, 5} examination indeed showed evidence of limited mutual solubility. Despite the great industrial importance of the nickel-rich alloys, only in the past ten years has the system been thoroughly investigated.

There is now general agreement that the system comprises a nickel-rich and a chromium-rich solid solution and that the mutual solubility decreases with the temperature although some divergence exists regarding the low temperature domain of the two solid solutions, particularly that rich in nickel.^{6, 7, 8} This is to be expected in view of the difficulty of attaining equilibrium at low temperatures and due to the effect of impurities; and some slight revision in this region is to be expected in the course of time.

The recent investigation of Jenkins and associates⁹ was conducted with great care and precautions were taken to exclude impurities; for this reason their data are accepted and shown in Fig. 1. The melting point of chromium indicated (1830°C.) is based on Adcock's¹⁰ determination and is higher than that observed by others^{4, 10} but ties in well with the melting temperatures of the alloys studied by Jenkins. The melting temperature of the eutectic is 1343°C. and at this temperature about 47% of chromium is soluble in nickel. At lower temperatures a small decrease in solubility occurs, slightly in excess of 40% chromium being soluble at 900°C. Thirty-five per cent nickel is soluble in chromium at the eutectic temperature, but a marked reduction in solubility occurs at lower temperatures—perhaps 9% being soluble at 900°C.

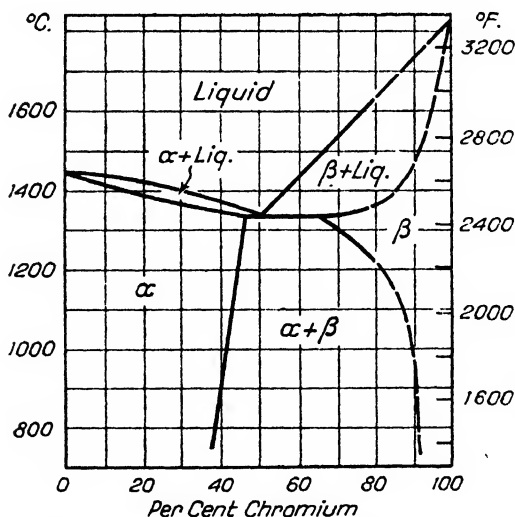


Fig. 1—Nickel-chromium constitution diagram.

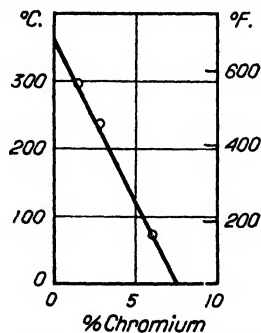


Fig. 2—Curie temperature of nickel-chromium alloys.

Due to the lack of determinations in a portion of the high temperature high chromium region plus the difficulties in high temperature thermometry, a portion of the liquidus and solidus has been dotted. Because of the difficulty in attaining

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equilibrium at low temperatures and the possible effect of nitrogen and other contamination, the solid solubility line is dotted.

The magnetic change point (Curie temperature) is rapidly lowered by the addition of chromium to nickel, but some disagreement exists in the precise relationship.^{4, 7, 12} The recent investigation of Marian¹³ yields the results shown in Fig. 2 which are tentatively accepted.

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Constitution of Nickel-Cobalt Alloys

By D. E. Ackerman*

The nickel-cobalt system was first studied by Guertler and Tammann¹ who found a continuous system of solid solutions, the solid alloys becoming nonmagnetic when heated above a critical temperature which increased with the cobalt content. The general features of the first investigation were confirmed by Ruer and Kaneko,² whose data on the temperatures of the magnetic transformation, liquidus and solidus are the most accurate. After correcting for the currently accepted values of the melting point and Curie temperatures of the pure metals these data have been plotted in Fig. 1. The liquidus rises slowly from 1455°C. at pure nickel to 1480°C. at pure cobalt; there is unanimous agreement that the liquidus and solidus nearly coincide and the single line (liquidus) shown on the diagram is to be considered as two lines having a maximum separation of possibly 2-3°C. at about 50% cobalt.

The Curie temperature rises continuously from 362°C. at pure nickel to 1125°C. at pure cobalt. Some doubt exists as to the exact Curie temperature of cobalt, various investigators^{3, 4, 5, 14, 17, 18, 19} reporting values varying from 1100°C.-1130°C. Strictly speaking, the Curie temperature curve in the figure marks the end of the magnetic transformation, alloys held at higher temperatures being nonmagnetic. The beginning of this transformation, which Ruer and Kaneko (as well as later experimenters) considered to involve no crystallographic change, is ill defined and rather dependent upon the details of the experimental technique and is therefore not indicated on the diagram. Steinwehr and Schulze¹¹ find the heat of the magnetic transformation to be 1.2 cal. per g.

In 1926 Masumoto⁷ announced the discovery of a new transformation in pure cobalt, the metal having a close packed hexagonal lattice at temperatures below about 400-440°C. and a face-centered cubic lattice at higher temperatures. Masumoto's four samples contained various amounts of impurities up to a maximum of 0.45%, chiefly nickel, iron, and carbon, the transformation temperature increasing somewhat with the purity of the specimen. The transformation was studied by means of thermal analysis, electrical conductivity, thermal expansion, magnetic tests, dilatometer tests and X-ray analysis. This transformation in pure cobalt has been observed by others (references 4-12, 17-21) and appears to occur at 440°C., although temperatures ranging from 399-475°C. have been given. Several investigators^{10, 14, 17} have commented upon the extreme sluggishness of the transformation from the hexagonal to cubic cobalt. This sluggishness is apparently related to the small heat of transformation (0.1 cal. per g.) found by Steinwehr and Schulze.¹¹

Masumoto's much less complete study of cast nickel-cobalt alloys annealed three hours at 1100°C. before testing, showed the temperature of this transformation to be depressed by nickel additions as shown by the boundary between the alpha and alpha + beta fields; the location of the alpha + beta, beta field boundary rests upon almost no experimental evidence; the boundaries between the alpha and the beta fields have not been checked to date and in view of the scanty and somewhat unreliable data upon which they are based their locations must be considered as tentative only.

The data of many investigators^{5, 7, 9, 10, 13, 14} suggest the existence of a structural transformation at some higher temperature, in the range of 800-1100°C., at which the face-centered cubic lattice formed at 440°C. again transforms to a hexagonal close packed lattice. These data are not concordant and their interpretation is complicated by the fact that structural transformations in cobalt are very sluggish and

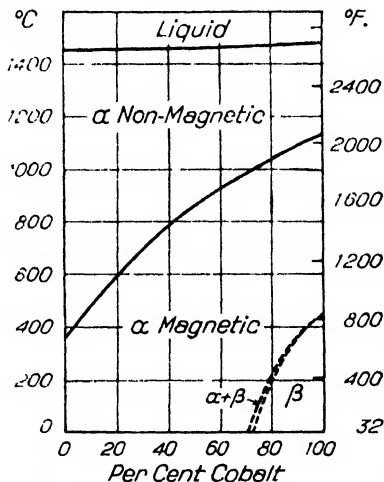


Fig. 1—Nickel-cobalt constitution diagram.

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are markedly influenced by mechanical work. The careful work of Seybolt and Mathewson¹⁴ seems to support Cardwell's¹³ conclusion (from room-temperature X-ray data on quenched cobalt) that a transformation exists at 850°C. Marick,¹⁵ on the other hand, recently studied Cardwell's cobalt and concluded, on the basis of X-ray examination at high temperature, that the 850°C. transformation is nonexistent. Again, Sykes,¹⁶ using the technique of Hendricks, Jefferson and Schultz⁷ was able to check the observation of the latter investigators that a transformation occurred at 1020°C. but could detect no transformation in the 800-1100°C. range in cobalt by thermal means. In general, different investigators have used both different methods of study and cobalt prepared in widely different ways and of widely different purities, and a critical study of these various possible sources of disagreement would be highly desirable, for even among those adhering to a belief in a high temperature transformation there is considerable divergence of opinion as to the actual temperature. At present the weight of opinion seems to favor one structural transformation point, that at 440°C.

The lattice constants of the nickel-cobalt alloys have been measured by Osawa,¹⁷ those of metallic cobalt have also been determined by Van Horn. Osawa's value of "a" for nickel is in excellent agreement with that of McKeehan;¹⁸ the divergence in the constants for pure cobalt may be related to the different methods used in preparing the specimens.

Lattice Constants of Nickel-Cobalt Alloys and of Cobalt

% Ni	Lattice	a	c	c/a	Investigator
100	Face-centered cubic	3.508	.....	.....	Osawa
20	Close packed hexagonal.....	2.489	4.036	1.621	Osawa
16	Close packed hexagonal.....	2.493	4.024	1.622	Osawa
10	Close packed hexagonal.....	2.493	4.046	1.623	Osawa
4	Close packed hexagonal.....	2.492	4.052	1.628	Osawa
0	Close packed hexagonal.....	2.492	4.056	1.631	Osawa
0	Close packed hexagonal.....	2.498	1.631	Van Horn
0	Face-centered cubic	3.525	Osawa
0	Face-centered cubic	3.512	Van Horn

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Constitution of Nickel-Manganese Alloys

By N. B. Pilling*

The nickel-manganese series has received attention from but few investigators even though the lower manganese content alloys are of some technological importance. The early (1908) diagram of Zemczuzny, Urasow and Rykowski¹ represented a continuous series of solid solutions with a minimum in the liquidus. Dourdine,² confirming the general aspects of the liquidus curve with a purer set of alloys, found (1915) microscopic evidence of heterogeneity in the range from 38-71% manganese and detected a complicated series of solid transformations within this same range. In this fragmentary state the diagram rested until quite recently.

Dourdine² resumed his study of this series and in 1932 published a revision of his earlier diagram. This is represented in Fig. 1. In many respects it must be regarded as tentative, yet it suggests the following relations. Mn dissolves in Ni, at temperatures exceeding about 760°C., up to 43%; at temperatures below this the solid solutions containing more than 36% Mn undergo a transformation which appears to produce the compound Mn_3Ni_4 or epsilon phase. At about 48% Mn the delta phase occurs, which at temperatures approaching the solidus, corresponds to the compound $MnNi$; the solubility of this phase for Ni changes but slightly with temperature down to 600°C., while its solubility for Mn increases greatly as the temperature decreases. It is subject to a transformation at about 600°C., the significance of which has not yet become clear. The solubility of Mn for Ni, at temperatures approaching 1000°C., extends down to about 58% Mn, the limiting concentration being that of the compound Mn_3Ni_4 . This gamma phase, at concentrations lower in Mn than about 68%, transforms into the delta phase. The compound Mn_3Ni_4 , therefore, exists only within the limited temperature range of approximately 950-1000°C. Two fields of duplex alloys occur (beta + delta) and (delta + gamma). The former is complicated by solid transformations affecting both phases; the limiting concentrations of the latter change considerably with temperature and have not as yet been traced out fully.

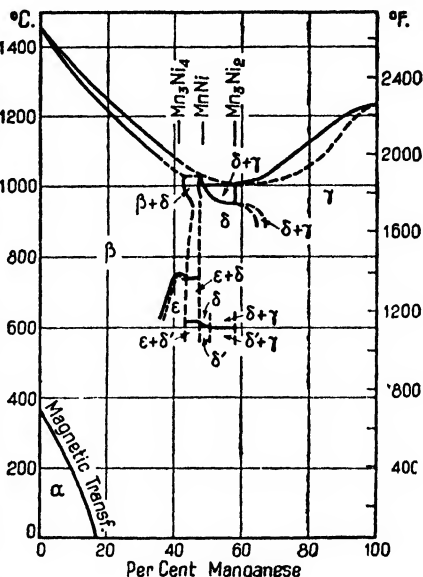


Fig. 1—Nickel-Manganese Constitution Diagram.

The constitution of the alloys quite rich in Mn has evidently not been studied. Manganese undergoes a number of transformations in the solid state, recent work³ indicating three modifications:

Alpha Mn	cubic	under 742°C.	8.894A
Beta Mn	cubic	742°-1191°C.	6.300A
Gamma Mn	tetragonal	above 1191°C.	{3.774A 3.526

Dourdine reports⁴ that under ordinary rates of cooling from solidification an unstable state persists, resulting in a fictitious appearance, of complete miscibility between Ni and Mn, the delta phase and related heterogeneous fields being suppressed. A more or less prolonged heating at temperatures in the vicinity of the solidus is required for the development of that state which permits the formation of the stable phases represented on the diagram.

Manganese depresses the magnetic transformation temperature of Ni,⁴ 17% Mn sufficing to lower it to room temperature. The alloys containing 12-40% Mn can

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be transformed⁷ by long heat treatment below 450°C. to a strongly ferromagnetic state, the change occurring without structural alteration.

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The Constitution of the Nickel-Molybdenum Alloys

R. H. Schaefer*

This system was first investigated by Baar¹ by thermal analysis and microscopical methods. He reported a nickel-rich solution of molybdenum, an eutectic at 1305°C. and 49% molybdenum, and the peritectic formation of the compound NiMo at 1345°C. and 62% molybdenum. Dreiholz² later confirmed the peritectic formation of the compound, but found the eutectic temperature to be 1315°C. He also determined the effect of molybdenum on the Curie temperature of nickel which was lowered to room temperature by the addition of 18% molybdenum.

At 1305°C. the solubility of molybdenum in nickel was placed at about 32% by Baar, based upon the appearance of a cooling curve arrest in a 35% molybdenum alloy which was not found in an alloy containing only 30% molybdenum. The limit of this alpha solid solution field was shown to decrease at lower temperatures by Koster and Schmidt,³ who reported a solubility limit of 18% molybdenum at 800°C.

Recently the first really comprehensive study of this system was published in two parts by Grube and Schlecht⁴ and Grube and Winkler,⁵ who discovered several

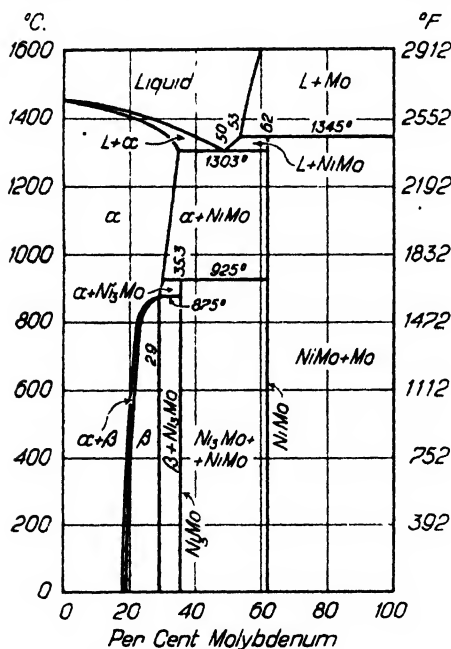


Fig. 1—Nickel-molybdenum constitution diagram.

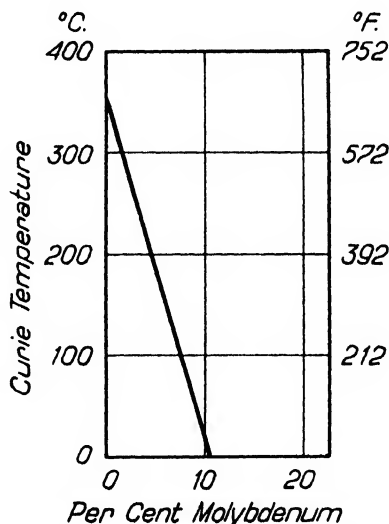


Fig. 2—Effect of molybdenum on the Curie temperature of nickel.

new fields. The alloys were prepared from quite pure nickel and molybdenum powders,[†] and carefully pressed and sintered.⁶ Depending upon the molybdenum content of the alloys, they were then cold rolled, hot rolled or heated to incipient fusion to seal any fissures, homogenized for 48 hr. at 1280°C., and furnace cooled to room temperature in from 10-14 days. As a result of hardness, electrical resistance, magnetic susceptibility, corrosion resistance measurements, X-ray and microscopical examination, they reported the constitution diagram which is reproduced in Fig. 1.

In general the above work agrees quite well with Baar's data at temperatures above 925°C., but below this temperature two new phases are reported. The face-centered cubic alpha solid solution starts to transform at 875°C. to an ordered face-centered tetragonal β phase which possesses a superlattice. A very small

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[†]The nickel contained 0.04% C., 0.12% Fe, 0.08% O₂, and was sulphur free. The molybdenum was 99.9% pure.

heterogeneous region $\alpha + \beta$ exists between the two fields. At room temperature the β field is shown to extend from approximately 18-29% molybdenum. The latter concentration happens to be approximately that of Ni_3Mo , so that the β phase might be considered to be a solution of nickel in Ni_3Mo . The dimensions of the unit cell of the 29% molybdenum alloy are reported to be $a = 3.61 \text{ \AA}$ and $\frac{c}{a} = 0.98$.

At 35.3% molybdenum and 925°C . a peritectoid reaction occurs between the alpha solid solution and the compound NiMo yielding the compound Ni_3Mo . The latter has a close packed hexagonal lattice with $a = 2.54 \text{ \AA}$ and $\frac{c}{a} = 1.65$. The compound NiMo which occurs at 62% molybdenum is said to have a very complicated structure which has not as yet been determined.

Grube and his co-workers attempted to determine by X-ray methods whether any solid solution occurred on the molybdenum end of the diagram. They found no increase in the lattice constant of pure molybdenum ($a = 3.1374 \text{ \AA}$) in alloys containing 1-20% nickel and therefore concluded that no appreciable solubility exists. However, the unpublished work of W. P. Sykes¹ and C. A. Brashares indicates that at 1400°C . approximately 0.5% nickel is soluble in molybdenum. The latter investigators also reported the eutectic and peritectic temperatures to be $1345 \pm 10^\circ\text{C}$. and $1400 \pm 10^\circ\text{C}$., respectively, which are somewhat higher than those found by Baar and Grube.

The effect of molybdenum on the Curie temperature of pure nickel is shown in Fig. 2. This is based upon the work of Marian² and Grube³, who agree that 10-11% molybdenum is necessary to lower the magnetic transformation to 0°C .

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Constitution of Nickel-Silicon Alloys

By D. E. Ackerman*

Only two investigations of the complete nickel-silicon system have been made; the first by Guertler and Tammann,¹ the second by Iwase and Okamoto.² The first study was based chiefly upon thermal and microscopical methods while the second utilized thermal analysis, microscopy, X-rays and magnetic analysis. Unfortunately, the published accounts of both researches fail to make clear what precautions, if any, were taken to insure that the specimens tested were in complete equilibrium. Comparison of data from several available studies of restricted portions of the diagram with those cited above give rise to some doubts as to the accuracy of the latter. While there is thus little specific grounds for choice, even between the

two available comprehensive studies, the data of Iwase and Okamoto have been chosen as the basis for the present diagram, chiefly because they are the more recent, the more numerous and were obtained by more different types of experimentation. Several features of the diagram (the course of the alpha field boundary and the existence of Ni_3Si and NiSi) are rather well established. Guertler, Iwase and Okamoto also postulate the existence, at some temperature, of Ni_2Si and Ni_5Si_3 , but the remainder of the diagram must be considered tentative only. The uncertainties are both qualitative and quantitative in nature. The data available up to 1936 have been critically reviewed elsewhere.³

The location of the high-temperature (800-1100°C.) portion of the α field boundary is based upon the careful X-ray work of Blumenthal and Hansen⁴ while the remainder of the boundary utilizes the data resulting from the painstaking hardness, electrical resistance and microscopical data of Dahl and Schwartz.⁴ The alloys used by the latter contained 0.5% manganese and 0.05% magnesium as deoxidizers. At room temperature the maximum solid solubility of silicon in nickel appears to be about 6.0%.

The liquidus curve for the system exhibits four eutectics as follows:

$\alpha + \beta$	melting at 1151°C. and containing 11.5% Si
$\text{Ni}_3\text{Si}_2 + \text{Ni}_2\text{Si}$	" " 1242 " " 17.5
$\gamma + \text{NiSi}$	" " 964 " " 29.0
$\text{NiSi} + \text{NiSi}_2$	" " 986 " " 38.0

Three intermetallic compounds which melt without decomposition are also indicated

Ni_3Si_2	melting at 1256°C. and containing 16.0% silicon
Ni_2Si	" " 1284 " " 19.3
NiSi	" " 990 " " 32.4

Two intermetallic compounds formed by peritectic reactions are also postulated:

$\beta(\text{Ni}_3\text{Si} + \text{Ni})$	formed at 1163°C. by reaction between Ni_3Si_2 and 12% Si melt
NiSi_2	" " 993 " " δ " 41.5% Si melt

NiSi_2 undergoes a polymorphic change at 981°C.

The α solid solution has been discussed. The presence of a β solid solution, consisting of Ni_3Si which may dissolve excess nickel, appears to be consistent with Iwase and Okamoto's data on duration of the thermal arrest at 1151°C., but no microscopical or other data supporting such a field have been presented; it is

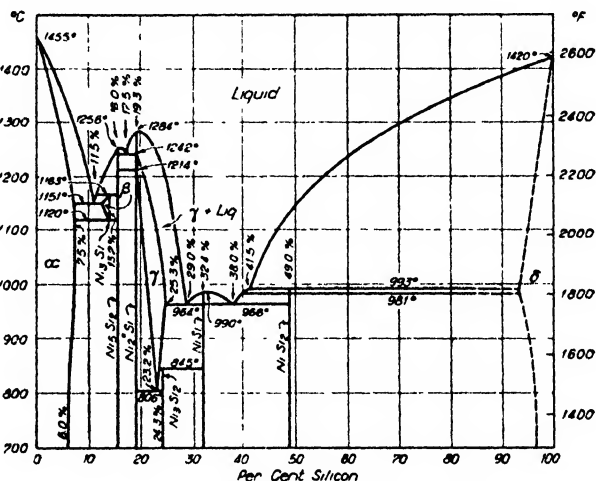


Fig. 1—Nickel-silicon constitution diagram.

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retained simply because it represents the most general case possible with the data available. β is indicated as decomposing eutectoidally at 1120°C. The γ solid solution may be considered to consist of a solid solution of silicon in Ni_3Si (which undergoes a polymorphic change at 1214°C). γ undergoes an eutectoid transformation at 806°C., yielding Ni_3Si and Ni_2Si ; the latter may form at 845°C. by a peritectoid reaction between NiSi and γ . None of the investigators of this system except Guertler¹¹ suggest the possible solid solubility of nickel in silicon, but a limited solid solution of nickel in silicon, designated δ , has been included in the diagram.

Oelsen and Samson-Himmelstjerna⁸ have obtained the heat of formation-composition curve and the heat content-composition curve for the system and find only two breaks which would indicate compounds which melt without decomposition. The heats of formation of these are:

Ni_2Si	33.6 kg. cal./g. mol.
NiSi	20.6 " " "

The identification of these two, and only these two, stable compounds supports these features of Guertler and Tammann's work. Apparently they obtained no evidence of the existence of the Ni_3Si proposed by Iwase and Okamoto. Oelsen and Samson-Himmelstjerna confirmed the existence of Ni_3Si , whose heat of formation is the sum of those of Ni_2Si and NiSi and which they therefore regard as a double silicide. They also confirm the existence of Ni_3Si and Ni_2Si , the latter being indicated on Guertler and Tammann's diagram but not on that of Iwase and Okamoto.

Many of the basic facts regarding the system are thus in dispute and a carefully conducted, comprehensive study of the system is required. It may be pointed out that the only study of the lattice constants of the various phases is the work of Boren⁷ who found NiSi to be structurally similar to FeSi (tetrahedral cubic) and to have a lattice parameter of 4.437Å although this value may be in error because of the diffusedness of the line edges.

Several determinations of the effect of silicon upon the Curie point of nickel are available; aside from the data of Manders,⁸ which are rather irregular, the data are fairly consistent although those of Dahl and Schwartz⁹ show a less rapid drop in Curie temperature with silicon content than the data of Kusemann and Scharnow¹⁰ and of Marian,¹⁰ both of which agree well with each other and with the data of Iwase and Okamoto.³ A weighted mean of the better data follows:

% Silicon	Curie Temperature
0	362°C.
1	320
2	263
3	195
4	130
5	45
6	-45

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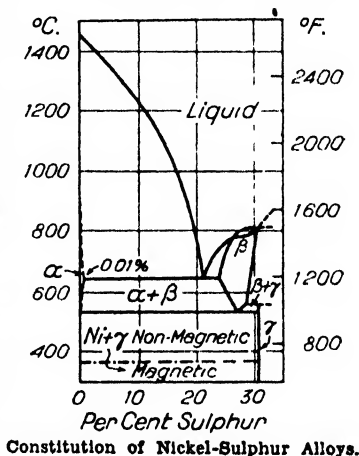
The Constitution of Nickel-Sulphur Alloys

By D. E. Ackerman*

The first and only study of the constitution of the binary nickel-sulphur alloys is that of Bornemann,¹ who examined nickel alloys containing from 0-31% sulphur. The sulphur volatilizes from richer melts too fast to permit study. The diagram was based almost entirely upon thermal analysis, although a few confirmatory microscopical examinations in some of the larger fields were made. Sulphur was found by Bornemann to have a maximum solubility of 0.5% in solid nickel at 644°C., but to be insoluble below 532°C. A strongly marked eutectic of alpha (solid solution of sulphur in nickel) and beta (solid solution containing Ni_3S_2) was found at 21.5% sulphur and 644°C. Between 24 and 31% sulphur and 520 and 810°C., the beta solid solution containing Ni_3S_2 occurred. At lower temperatures but at the same sulphur contents a considerable number of phase fields of restricted area were indicated, but the existence of these may be questioned, since it is not clear that the pretreatment of the specimens was such as to insure freedom from segregation, which, at the sulphur contents involved, might be expected to be present in the original castings on a considerable scale. The reality of the thermal arrests upon which these small fields were based cannot be questioned, but it may be suggested that some of them originated in the successive transformation of variously segregated regions in each of the several specimens.

The eutectic at 21.5% sulphur and 644°C. has been directly observed by several investigators, among whom may be mentioned Hayward,² Vogel and Tonn,³ and Merica and Waltenberg,⁴ and has been inferred by others.^{4,5} As the result of a study of portions of the ternary iron-nickel-sulphur system Guertler and Savelsberg⁶ have, by extrapolation, suggested a binary nickel-sulphur constitution diagram which differs, particularly in the higher sulphur ranges, from that of Bornemann. Unfortunately, few experimental details are given.

The accompanying constitution diagram is based chiefly upon the work of Bornemann and of Guertler and Savelsberg, although the careful work of Merica and Waltenberg has been taken into consideration in provisionally locating the limits of the alpha field. The latter investigators, working with unhomogenized, cast nickel-sulphur alloys, found the eutectic arrest at 644°C. in alloys containing more than about 0.03% sulphur, but could detect heterogeneity by microscopic examination with as little as 0.005% sulphur. These data suggest, first, that at low sulphur contents the microscopical method may be more sensitive than the thermal method, relied upon by Bornemann for determining the range of the alpha field. Second, the true solid solubility of sulphur in nickel must be considerably lower than reported by Bornemann. The presence of microscopically visible sulphide in the 0.005% sulphur, as cast specimens of Merica and Waltenberg, may be ascribed to a local sulphur content, produced by segregation effects, in excess of the solid solubility limit. In view of the low nominal sulphur content and the small size of the melts it appears quite improbable that local sulphur contents resulting from segregation would be more than twice the average sulphur content. A value of 0.01% sulphur is thus suggested as the solid solubility of sulphur in nickel at 644°C. While this value has been used in the diagram it should probably be considered as the upper limit of the possible solid solubility, for the forging tests of Merica and Waltenberg and of others indicate that the value should be even lower. The insolubility of sulphur in nickel below about 532°C. is based almost entirely upon the general nature of the diagram and upon the fact that, according to Bornemann, the Curie point of nickel is not shifted by moderate sulphur contents.



Constitution of Nickel-Sulphur Alloys.

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As mentioned above, the eutectic of alpha (whether nickel or a dilute solution of sulphur in nickel) and beta at 21.5% sulphur and 644°C. is well established. The beta phase is a solid solution containing the compound Ni_3S_2 , the latter solidifying at 787°C. Because of the lack of experimental data the exact nature of the solid alloys, containing higher sulphur contents than the beta phase, is not known, but a solid solution apparently exists which decomposes at 550°C. with the formation of a compound, possibly Ni_2S_3 , which has been designated gamma. The beta phase breaks down at 532°C. with the formation of nickel and gamma, the nickel undergoing a magnetic transformation at 362°C.

The liquidus is probably reasonably accurate from 0 to about 31% sulphur. The existence of the compound Ni_3S_2 is established. Alsen⁶ suggests it is cubic, with a value of $a = 4.08 \text{ \AA}$. The existence of the beta phase, but not, necessarily, its compositional range, may be accepted, and the same is true of the solid state transformations at 644°C. and at 532°C. The remainder of the diagram, including the nature and limits of the alpha phase, require further study. Indeed, a recheck of the entire system, using several modern methods for determining the extent of each of the several fields, would be most interesting, as the application of the now well developed theory of pressure-temperature-composition diagrams should permit extension of the binary diagram to considerably higher sulphur contents.

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Constitution of Nickel-Tin Alloys

By J. T. Eash*

The nickel-tin system has been the subject of few investigations. Complete diagrams were reported by Gullet¹ in 1907 and by Voss² in 1908. Renewed interest has been shown in these alloys in recent years and in 1937, Mikulas, Thomassen and Upthegrove³ reported the results of their investigation of the complete system. While the interpretations given the diagrams of the three studies are quite different, the liquidus, the eutectic and peritectic temperatures agree fairly well. Jette and Fetz⁴ determined the limit of solubility of tin in nickel in 1935.

The constitution diagram shown in Fig. 1 is chiefly as given by Mikulas, Thomassen and Upthegrove.³ Thermal analyses, microscopic and X-ray examinations were used for the determinations. Hanson, Sandford and Stevens⁵ report the occurrence of a eutectic at 0.18% nickel at 232°C., the melting point of tin, between tin and a compound; however, Mikulas and associates found no evidence of a eutectic microstructure and conclude from analyses of quenched specimens the eutectic must contain less than 0.01% nickel.

The compound Ni_3Sn , containing 27.1% nickel is formed at 793°C. by the peritectic reaction with liquid and Ni_3Sn_2 . It has a density of 8.78. Mikulas reports it as having a complex lattice structure which was not determined. Fetz and Jette⁴ indicate that the phase probably exists over a narrow composition range.

By means of X-ray examinations, Fetz and Jette found a phase at 29.7% nickel which they called theta; however, they give no information regarding the mechanism of its formation.

Vigouroux⁶ was able to separate residues from two alloys by chemical methods and found them to contain 33.3% nickel which would correspond to the compound Ni_3Sn . From X-ray investigations, Oftedal⁷ and Fetz and Jette report the presence of phases corresponding to Ni_3Sn ; however, Mikulas found that an alloy of the Ni_3Sn composition which had been annealed 500 hr. at 500°C. contained two microscopic phases and concluded they were Ni_3Sn , and Ni_3Sn_2 .

At 43% nickel, Ni_3Sn_2 is formed. According to Mikulas it solidifies at 1253°C. Above 902°C. it has a body-centered tetragonal lattice structure with 10 molecules per cell where $a = 9.199$ Å, $c = 8.578$ Å and $c/a = 0.933$. Its density is 9.36. Below 902°C. it has a hexagonal modified nickel arsenide type of structure with 1 molecule per cell and $a = 4.092$ Å, $c = 5.186$ Å and $c/a = 1.267$ Å. Its density is 8.99.

The dotted line at 902°C. in the Ni_3Sn_2 + liquid field has been inserted by the writer to indicate the crystal change in the Ni_3Sn_2 phase which is inferred by the adjacent area of the diagram, but not shown in the literature.

The compound Ni_4Sn containing 60% nickel is formed at 1164°C. by the peritectic reaction between liquid and Ni_3Sn_2 .⁸ It has a density of 9.62. P. Rahlfs⁹ reports Ni_4Sn as having a hexagonal close packed lattice with a superstructure where $a = 2a = 5.275$ Å, $c = 4.234$ Å and $c/a = 1.606$. Fetz and Jette believe that both Ni_3Sn_2 and Ni_4Sn exist over very narrow composition ranges.

The peritectic reaction at 1143°C. between Ni_4Sn and liquid forms the compound Ni_5Sn containing 66.4% nickel. Ni_5Sn has a simple tetragonal lattice with 2 molecules per cell where $a = 5.111$ Å, $c = 4.881$ Å and $c/a = 0.955$. Its density is 9.15. Below 941°C. Ni_5Sn is unstable and forms Ni_3Sn and alpha solution.¹

The solubility of tin in nickel¹ decreases from about 18% at the eutectic temperature to 1.6% at 450°C. Jette and Fetz found that as a result of the change

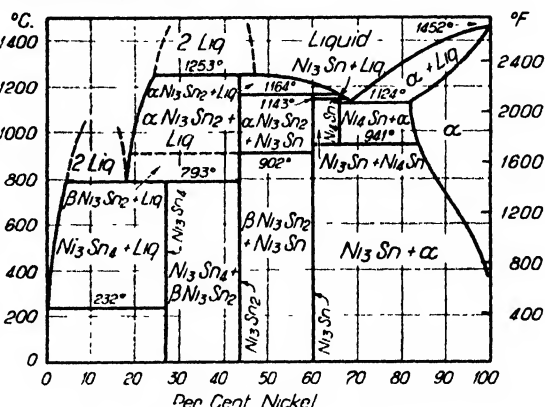


Fig. 1—Nickel-tin constitution diagram.

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in tin solubility with temperature, the alloys exceeding the alpha phase boundary could be age hardened. An alloy containing 20% tin had a hardness of 250 Brinell after quenching from 1050°C. and after aging 5 hr. at 600°C. a hardness of 490 Brinell.

The alpha solution has a face-centered cubic structure and its lattice parameter increases linearly from 3.515 Å to 3.602 Å between zero and 18.4% tin.^{3,4}

The magnetic transformation of nickel (358°C.) is lowered by the addition of tin as noted by Marian¹⁰ and others.^{1,2}

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Constitution of Nickel-Zinc Alloys

By D. E. Ackerman*

The first attempt to determine the constitution of the nickel-zinc alloys appears to be that of Tafel,¹ who published a series of three papers on the subject, the first of which appeared in 1907. Binary alloys containing 50-100% zinc were studied, chiefly by thermal analysis, with some microscopical data. An eutectic was found at 418.5°C. (the melting point of zinc being taken as 419°C., that of copper as 1084°C.) and it was suggested that the eutectic point occurred at about 99.75% zinc; the liquidus then rose with decrease in zinc content to 873°C., where it became horizontal at about 77.5% zinc, rising again with further decrease in zinc content. The existence of the compounds NiZn and Ni₂Zn, was suggested and four horizontals below the liquidus were also located, as follows:

Temp., °C.	Range, % Zinc
418.5	100-88
640	70-54
780	53-50
870	72.5-61

As will be seen later, the designation of the higher zinc eutectic temperature as 418.5°C. is in close agreement with the best present day determinations. At higher temperatures and lower zinc contents Tafel's data become somewhat too low, the liquidus temperature at 60% zinc (1010°C.) being about 10° lower than, and the 780°C. horizontal about 25-30°C. below, the best recent data. These discrepancies appear to be due chiefly to insufficient precautions to insure complete equilibrium in the alloys before beginning the experimental work.

In his later papers Tafel attempted to predict the nature of the low zinc end of the binary diagram from data obtained in the study of the ternary copper-nickel-zinc alloys, and while this extrapolation provided, for many years, the only information available on this part of the diagram, it could not supply the need for direct experimental data. Nevertheless, Tafel's diagram foreshadowed the present diagram with considerable fidelity, and though far from complete is ample testimony to Tafel's experimental skill and theoretical intuition.

In 1908 Voss² examined the alloys containing 100-77% zinc; he confirmed the shape of Tafel's liquidus in this range except that he appears not to have found the eutectic at 99.75% zinc and thought the 418°C. horizontal to extend from 100-85.5% zinc.

Bornemann³ discussed some of the shortcomings of the work to date but supplied no constructive suggestions. Peirce⁴ found the high zinc eutectic at about 99.75% zinc and 419.4°C. and suggested a small (0.05%) solubility of nickel in zinc. Charrier⁵ reported a number of nickel-zinc compounds, not all of which are now thought to exist. Hafner⁶ suggested several changes in the diagram, but his data appeared not to warrant a modification of the latter. The constitution diagram which appeared in the International Critical Tables⁷ at about the same time was in close agreement with the diagram suggested somewhat later by Bauer and Hansen,⁸ who subjected the available information to an enlightening critical review which revealed the slender basis of experimental data upon which the accepted constitution diagram rested.

In 1932 Tamaru,⁹ and Heike, Schramm, and Vaupel,¹⁰ published their independent researches on the system; some of these data have been critically reviewed.¹¹ Tamaru

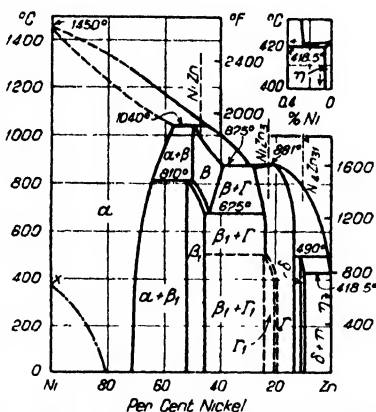


Fig. 1—The nickel-zinc constitution diagram.

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and Osawa¹² re-examined the high zinc end of the diagram in more detail. Comparison of these reports reveal numerous discrepancies, some of major and others of minor importance; many of these appear to arise from the rather casual precautions taken in the Japanese work to avoid loss of zinc, to insure homogeneity and to minimize other similar sources of error. The rather satisfactory resolution and elimination of most of these discrepancies recently has been accomplished on theoretical and experimental grounds by Heike, Schramm and Vaupel¹³ and by Schramm¹⁴ and the diagram resulting from their careful work is the one offered here, although it is tentative in several respects.

The alpha solid solution extends from 0-28% zinc at room temperature and to 43.3% zinc at 1040°C. Heike, Schramm and Vaupel consider the β phase, which forms by a peritectic reaction at 1040°C. between saturated alpha solid solution and melt containing 55% zinc, to be a conventional solid solution. Below 810°C. to 675°C. (as the zinc content varies from 48-55%) there exists a β_1 phase the exact nature of which (whether a simple solid solution or, essentially, a compound NiZn) is not yet clear. The gamma phase consists of a solid solution based upon an intermetallic compound assumed, in this diagram, to be NiZn, though some investigators consider the basic compound to be $\text{Ni}_4\text{Zn}_{11}$ or $\text{Ni}_7\text{Zn}_{10}$. The gamma phase melts without decomposition at 881°C.; its compositional range shifts considerably with temperature. Below about 500°C. the gamma phase transforms into a Γ_1 phase if the zinc content is below 80%. This transformation was discovered by Schramm and requires some further work for its complete elucidation. The delta phase is an intermetallic compound $\text{Ni}_4\text{Zn}_{11}$, containing 10.4% nickel and forms as the result of a peritectic reaction at 490°C. between the saturated gamma solid solution (14.4% Ni) and the melt (ca. 2.0% Ni). This compound may hold a very small amount of excess nickel in solid solution. A nickel-rich solid solution containing up to 0.05% zinc comprises the eta phase; the solid solubility of zinc in the saturated solid solution is thought not to change with temperature. An eutectic between delta and eta occurs at 418.5°C. and 99.75% zinc.

The data of three groups of investigators^{9, 10, 11, 12, 14, 15} bear on the crystallographic nature of the various phases. The data of Caglioti and of the Japanese investigators are open to some question as it is not certain that proper precautions to insure constant composition and equilibrium conditions were taken in every case. The data of the German authors appear the most reliable though they are checked, in several instances, by data from the other sources.

The alpha phase is face-centered cubic, with a lattice parameter, for the saturated solid solution at room temperature, of 3.576 Å. The β phase cannot be retained at room temperature by quenching; high temperature X-ray analysis shows this phase to be body-centered cubic (CsCl type) with a lattice parameter of 2.908 Å. The β_1 phase is body-centered tetragonal, the lattice parameter-composition curves showing a maximum for "a" (2.7458 Å) and minima for "c" and "c"/"a" (3.1739 Å and 1.1559 respectively) at 52% zinc, the composition of the hypothetical compound NiZn. The lattice of the gamma phase is cubic, with 52 atoms in the unit cell; that of the Γ_1 phase is very similar and can be obtained by a very slight deformation of the gamma lattice. The lattice of the delta phase ($\text{Ni}_4\text{Zn}_{11}$) is hexagonal ($a = 8.855$ Å, $c = 14.603$ Å) and is likewise considered to be deformationally derivable from the gamma phase lattice.

The data on the effect of zinc upon the Curie temperature of nickel are taken from what appears to be the best⁹ of the several sets of data^{9, 10, 11} available on this point.

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Physical Constants of Pure Nickel

By G. F. Geiger*

Introduction—The purity of electrolytically refined nickel is approximately 99.95% (includes cobalt). Electrolytically refined nickel of special purity, 99.99%, containing no cobalt, has been made in small quantities.¹⁴

The values assigned for the various physical constants or properties of metals are approximations only, based upon the best data available. Since the composition and structure of metals vary any single value assigned is estimated to be a typical or average value and should not be accepted as minimum, maximum, or specification values.

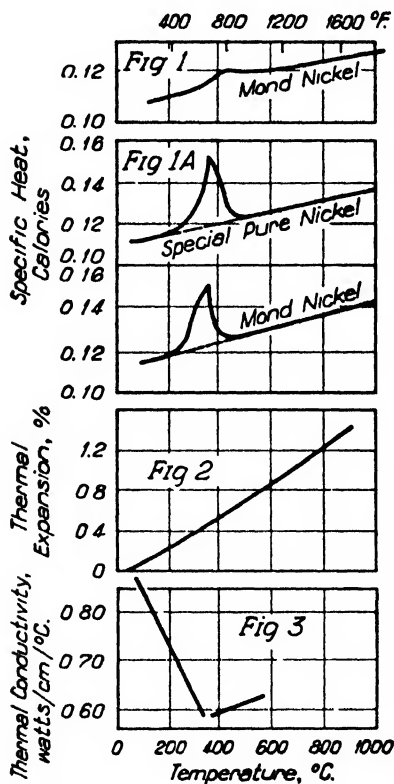


Fig. 1—Mean specific heat (0-20°C.) of Mond nickel (Umino).

Fig. 1A—True specific heat of pure nickel and Mond nickel (Umino).

Fig. 2—Thermal expansion of 99.94% nickel.¹⁴

Fig. 3—Effect of temperature on thermal conductivity (99.94% Ni).

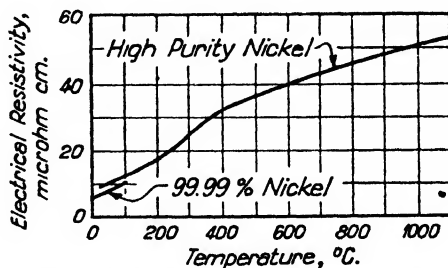


Fig. 4—Electrical resistivity of 99.99% nickel.

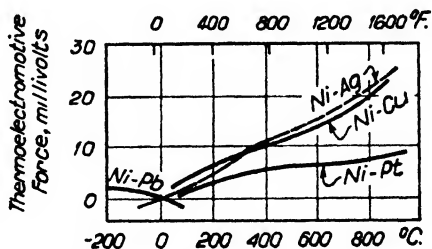


Fig. 5—Thermoelectromotive force of nickel. Note Ni-Ag—on nickel wire no analysis given. Ni-Pt—calculated from results on the Ni-Ag and Ag-Pt. Ni-Cu on nickel wire of the composition: Cu 0.20, Co 0.15, Fe trace, C + Si none, impurities 0.35. Ni-Pb on Mond nickel.

Atomic Weight—The atomic number of nickel is 28. The atomic weight according to the American Chemical Society is 58.69. Two isotopes of nickel are known—58 and 60.

Atomic Radius—The atomic radius of pure nickel is 1.38×10^{-8} cm.²

Crystal Form—The crystal form of nickel is face-centered cubic at all temperatures. The edge of the cube³ is 3.51 Å (3.51×10^{-8} cm.).

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(a) Single or limited number of determinations. (b) Average of many determinations.

¹⁴All references given at the end of the article on Properties of Commercially Pure Wrought "A" Nickel.

Density—The density (a) of pure nickel¹ (99.94%) is as follows:

Condition	Temperature, °C.	Density, g./c.c.
As cast	23	8.907
Cold swaged 23% reduction of area.....	25	8.901
Cold worked annealed at 950°C.....	25	8.902

Thermal Expansivity—The thermal expansion of pure nickel is shown in Fig. 2.

Freezing Point—The freezing point of a pure nickel²⁰ (b) (Fe .024, Cu .016, Co .016, Ni 99.94, C .005) is 1455°C.

Boiling Point—The boiling point of nickel is approximately²¹ 3377°C.

Vapor Pressure—The vapor pressure²² of pure nickel is shown below:

Vapor Pressure, mm. of Hg

Temp. °C.	mm. of Hg	Temp. °C.	mm. of Hg
327	1.315×10^{-23}	1127	2.83×10^{-5}
427	4.92×10^{-19}	1227	2.205×10^{-4}
527	1.493×10^{-15}	1327	1.306×10^{-3}
627	7.26×10^{-12}	1427	6.3×10^{-3}
727	1.005×10^{-10}	1527	2.4×10^{-2}
827	5.55×10^{-9}	1727	2.17×10^{-1}
927	1.552×10^{-7}	1927	1.275
1027	2.57×10^{-6}	2127	5.47

Specific Heat—The true and mean specific heat of a special pure nickel and cobalt free nickel is shown in Fig. 1 and 1A.

Thermal Conductivity—The effect of temperature on thermal conductivity¹⁴ of 99.94% nickel is shown in Fig. 3. The mean¹ (a) value from 0-100°C. is 0.140 cal./sec./sq. cm./°C./cm.

Optical Properties—The reflectivity¹⁰ of highly polished pure nickel (melted and solidified in vacuum) is as follows:

Wave length ¹⁰ of light in microns ($\mu = 0.001$ mm.) ^a	Per Cent
0.25 μ	47.5
0.30	42.0
0.35	45.0
0.40	52.0
0.45	57.5
0.50	62.0
0.55	64.0

Electrical Resistivity—The electrical resistivity of 99.99% nickel is shown in Fig. 4 and is also given in microhm-cm.²² as: R_0 6.141; R_{20} 6.844; and R_{100} 10.327.

The temperature coefficient from 20-100°C. is .00636 per °C.

Electrochemical Equivalent—The electrochemical equivalent of bivalent nickel, using an atomic weight of 58.69, is .0304 mg. per coulomb.

Electrolytic Solution Potential—The single potential of nickel at 25°C. is -0.231 volts (a) on the hydrogen scale.⁹

Thermoelectromotive Force—The thermal electromotive force of nickel against Ag, Pt, Cu and Pb is shown in Fig. 5.

The electromotive force developed is such that the current flows at 0°C. junction from the Ag, Cu or Pt to the Ni, when the emf. is +.

Magnetic Properties—Nickel exhibits no phase transformations. The metal is ferromagnetic below about 360°C. and paramagnetic above that temperature. This magnetic transformation is not accompanied by any change in crystal structure. The temperature of the magnetic transformation is affected by the composition. It is lowered by elements such as copper, carbon, silicon and manganese, up to their limit of solid solubility. This transformation is raised by iron and cobalt.

Physical Properties—The physical properties of unfused electrolytic 99.99% nickel wire, .063 in. dia.¹⁴ (a), hydrogen annealed at >2000°F. for 28 hr., cold drawn 50% and annealed at approximately 1400°F. for $\frac{1}{2}$ hr., are as follows: Proportional

Normal induction...See Fig. 6.

Magnetic permeability¹² (a) $H = \dots$ 1 Gilbert per cm. $\mu = 400$
 10 " " " $\mu = 400$
 100 " " " $\mu = 60$

Maximum permeability = 550
 (B = 2200 gauss).

Coercive force¹³ (a)
 (B = 5,000 gauss).....2.73 Gilbert per cm.

The heat of magnetic transformation¹⁴ (a) is
 2 cal. per g.

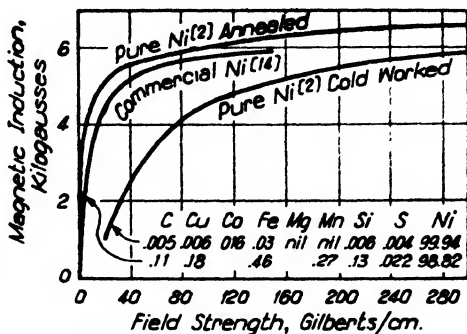


Fig. 6—Normal induction of nickel.

limit, 4,500 psi.; yield stress 0.1% offset, 7,500 psi.; yield stress 0.2% offset, 8,500 psi.; tensile strength, 46,000 psi., and elongation in 2 in., 28%.

Hardness—99.99% nickel,¹⁴ as electrodeposited, has a hardness of 282 Vickers. As annealed in H, for $\frac{1}{2}$ hr. at 1470°F., it has a hardness of 92 Vickers. As annealed in H, for 28 hr. at 2000°F., it has a hardness of 64 Vickers.

Properties of Commercially Pure Wrought "A" Nickel

By G. F. Geiger*

Composition—Commercially wrought nickel has a purity of approximately 99.40%, including cobalt. The following composition is typical: nickel plus cobalt 99.40, carbon 0.10, silicon 0.05, sulphur 0.005, copper 0.10, iron 0.15, manganese 0.20.

Metallographic Structure—The metallographic structure of nickel is typical of that of pure metals. When annealed, it shows a simple polyhedral crystal structure; the grain size of which depends upon the previous thermal and deformation treatment. When annealed after cold working, the metal twins readily and twinning is a prominent microstructural feature of many of the commercially available forms of wrought nickel.

Density—The density¹ (b) of nickel in the wrought form is 8.85 g. per cc. The weight per cubic inch used in commercial calculations is 0.319 lb.

Melting Point—The melting point² of commercial nickel (approximately 99.40%) is 2615-2635°F.

Latent Heat of Fusion—The latent heat of fusion of nickel³ is (a) 73 cal. per g. (131.4 B.t.u. per lb.).

Specific Heat—The mean (a) specific heat⁴ values for commercial nickel are:

Temperature Range, °C.	Specific Heat, cal. per g.
20-300	0.112
20-420	0.118
20-1000	0.126
20-melt. point	0.134

Electrical Resistivity—The electrical resistivity of "A" nickel and electrolytic nickel at different temperatures is shown in Fig. 1. The electrical resistivity of commercial nickel¹ (b) is 9.40 microhm-cm. at 20°C. The temperature coefficient from 20-100°C. determined on the same material is 0.00474 per °C.

Curves showing the resistivity temperature relation for various types of nickel are given in reference 24.

Thermal Conductivity—The thermal conductivity of commercial nickel expressed in watts cm.⁻¹ deg.⁻¹ as determined by S. M. Shelton and W. H. Swanger is as follows:

	Temperature, °C.				
	100	200	300	400	500
Thermal conductivity ⁵	0.828	0.732	0.638	0.593	0.621

*1 watt cm.⁻¹ deg.⁻¹ = 0.239 cal./sec./sq. cm./°C./cm.
 1 watt cm.⁻¹ deg.⁻¹ = 57.9 B.t.u./hr./sq. ft./°F./ft.

Thermal Expansivity⁶—The thermal expansivity of commercial nickel from 25-100°C. is 0.000013. (80-212°F. is 0.0000072.)

Tensile Properties—The average tensile properties of hot rolled and cold drawn "A" nickel rods are given in Fig. 2, and the average tensile properties of "A" nickel sheet and strip are given in Fig. 3.

Effect of Temperature⁷—Slight oxidation starts at approximately 575°F. At higher temperatures, a thin tenacious oxide film forms which permits, in some applications, the use of nickel at temperatures up to 2300°F.

The strength of hot rolled nickel increases with decrease in temperature. The

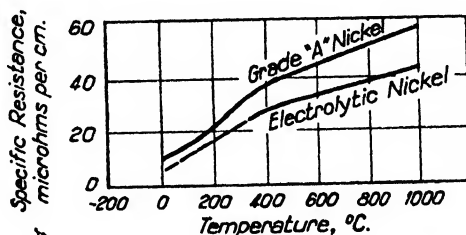


Fig. 1—Electrical resistivity of nickel at different temperatures.

*Development and Research Div., The International Nickel Co., Inc., New York.

(a) Single or limited number of determinations. (b) Average of many determinations.

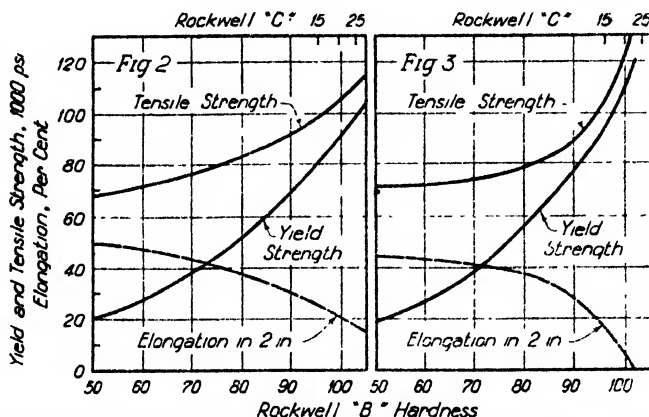


Fig. 2—Average tensile properties of hot rolled and then cold drawn nickel rods.

Fig. 3—Average tensile properties of nickel sheet and strip.

tensile and impact properties of hot rolled nickel at subatmospheric temperatures are shown below:

Temperature, °F.	Tensile Strength, psi.	Izod Impact, ft.-lb.
70	65,600	89
-112	76,500	92
-292	98,000	98

Table I gives the properties of nickel at elevated temperatures determined by short time tension tests.

Table I

Short Time Tensile Properties of Hot Rolled, Annealed Nickel (b)

	Temperature, °F.												
	70	150	300	400	450	600	700	800	1000	1200	1500	1775	
Yield strength 0.2% offset, psi.	23,700	21,750	21,875	21,375	21,000	21,000	21,125	19,625	16,875	15,250	9,250		
Tensile strength, psi...	72,750	74,500	74,875	75,000	77,375	79,000	81,625	77,000	40,000	32,875	22,125	7,125	
% Elongation in 2 in...	50.5	54.75	48.0	45.25	49.0	46.5	47.0	51.25	51.0	51.25	63.0	90.5	
% Reduction of area...	75.2	75.65	71.85	71.3	67.5	75.1	73.85	74.75	93.7	93.7	91.15	100.0	

Compression—Under compression loads, nickel takes a permanent set without fracturing. Compression values with corresponding tensile and hardness values are given in Table II.

Table II

Compressive Strength of Hot Rolled Nickel

Nickel	Compression	Tension		Hardness			
	Yield Strength 0.2% offset, psi.	Yield Strength 0.2% offset, psi.	Tensile Strength, psi.	Elongation % in 2 in.	Brinell 3000 kg.	Vickers 30p	Rockwell B
Hot rolled	23,150	24,000	71,000	44.5	107	116	89
Cold drawn 24% and stress relief annealed	58,350	62,000	86,650	33.0	177	190	80
Cold drawn and annealed 3 hr. at 1350°F.	26,200	26,650	73,250	46.0	109	115	49

Torsion—An important property of commercial nickel is the extremely large angle of twist before fracture occurs. The torsional properties¹⁴ of cold drawn commercial nickel tested in the full size rods are as follows:

	1½ in. diameter	1 in. diameter
Proportional limit, psi.....	47,800	52,700
Johnson's apparent elastic limit, psi.....	63,000	61,600
Ultimate strength, psi.....	81,400	
Angle of twist, deg./in.....	341	
Shear twist, in./in.....	2.97	

Impact¹⁴—Impact values are as follows:

Condition	Izod., ft.-lb.	Charpy Tension, ft.-lb.	Charpy Torsion, ft.-lb.	Charpy Impact, 45° V Notch, ft.-lb. —Temperature, °F.—		
				70	-112	-310
Hot rolled	120	29	98	195	236	227
Cold drawn 24% stress relief annealed	120	35	88	190	236	208
Cold drawn annealed 3 hr. at 1350°F.	120	29	113	216	236	234

Modulus of Elasticity—The moduli of elasticity of commercial nickel in tension is 30,000,000 and in torsion 11,000,000.

The variation in moduli due to cold working is insignificant; however, changes of temperature may have a marked effect.

Hardness¹⁴—The hardness ranges for the various tempers are as follows:

Temper	Rockwell B
Dead soft	Under 58
Soft	58-64
Skin hard	65-70
¼ hard	71-79
½ hard	80-85
¾ hard	86-91
Hard	92-98
Full hard	Over 98

Endurance Limit—The endurance limit for nickel depends upon the state of the material. The following figures expressed in psi. were obtained on the rotating cantilever type of machine at 100,000,000 cycles.¹⁴ Annealed 30,000, hot rolled 33,000, and cold worked 50,000.

Pouring Range—In the production of nickel ingots, the metal is teemed in the range of 2800-2890°F.

Heating—Nickel and high nickel alloys should be placed in a hot furnace and removed on a rising temperature. The atmosphere should be maintained reducing and should be as low as possible in sulphur content.

Forging and Hot Rolling—The recommended temperature range for hot working nickel is 2300-1200°F. As the temperature falls the percentage reduction should be decreased. Work below 1200°F. should be considered as cold work. The best hot bending range is between 2250-1900°F.

Cold Working—The cold rolling or drawing of nickel is, in many respects, similar to that of steel. In cold rolling, hardened steel rolls are used and in cold drawing, hardened steel dies and mandrels chromium plated and highly polished are used. While cold rolling is usually carried out dry, lubricants, such as water soluble or oil soluble types, are used in cold drawing operations. Regardless of the type of lubricant, it should be thoroughly removed before annealing.

Annealing—Small parts may be annealed in regular annealing boxes. A reducing atmosphere should be maintained within the box. When open annealed, a reducing atmosphere should be maintained within the furnace and to facilitate pickling, the work should be quenched directly from the furnace in a 2% denatured alcohol water solution. If an oxide film is not objectionable, the work may be water quenched or air cooled. The annealing temperatures are as follows:

	For Softening, °F.	Time at Tempera- ture	Stress Relief		Time, hr.
			For Highly Stressed Material, °F.	For Low Stressed Material, °F.	
Open	1250-1350	2-6 hr.	650-700	900-1000	1-2
Box or closed	1500-1700	15-1 min.	650-700	900-1000	1-2

Machining—The machining of commercial nickel is covered in the article under "Machining the High Nickel Alloys."

Pickling—The type of pickle required will depend upon the previous heating and cooling operations and the desired finish.

1. White surface free from oxide.

a. Bright annealed white metal requiring removal of tarnish by flash pickle.

b. Bright annealed metal requiring the removal of a layer of reduced metal, followed possibly, by flash pickle to brighten.

Flash Pickle—

Water	1 gal.
Sulphuric acid 68° Baumé.....	1½ gal.
Nitric acid 38° Baumé.....	2¼ gal.
Allow to cool for several hours and then add—	
Common salt	¼ lb.

The parts should be dipped in warm water and then immersed in the pickle for 5-20 sec. This should be followed by a hot or cold water rinse, a neutralizing dip in dilute ammonia and washed in hot water.

Pickle for Bright Annealed Nickel—

Water	7 gal.
Sulphuric acid 60° Baumé.....	5 qt.
Sodium nitrate, crude.....	7.5 lb.
Sodium chloride, commercial.....	7 lb.
Add water to make.....	10 gal.
Acidity at start, 15-18%; when dumped, 3½ to 4%.	
Baumé at start, 8°; when dumped, 25-30°.	
Temperature	180-190°F.
Time	20-60 minutes

2. Green or dark colored surface requiring removal of adherent oxide film.

Pickle for Removing Oxide Film from Nickel—

Hydrochloric acid 30° Baumé.....	1 gal.
Water	2 gal.
Cupric chloride	½ lb.
Temperature	180°F.
Time	1 to 2 hr.

Grinding, Polishing and Buffing—The grinding, polishing and buffing of commercial nickel is covered in the section under "Grinding, Polishing and Buffing High Nickel Alloys."

Welding and Soldering—All the welding methods commonly used may be used on nickel. These include oxy-acetylene, metallic and carbon arc, flash, spot and atomic hydrogen welding. This subject, including silver soldering and soft soldering, is covered in detail in a separate article.

Available Forms—Nickel is produced in the usual wrought forms—sheet, plate, strip, tubing, rod, wire and other shapes. These are produced by the usual hot rolling, cold rolling, and cold drawing processes.

Corrosion Resistance—Nickel does not readily discharge hydrogen from any of the common acids. A supply of some oxidizing agent, such as dissolved air, is necessary in order for corrosion to proceed. Reducing conditions usually retard corrosion of nickel, while oxidizing conditions accelerate corrosion. However, nickel has the ability to protect itself against certain forms of attack by development of a corrosion resisting, or passive, oxide film, and, consequently, oxidizing conditions do not invariably accelerate corrosion.

Atmospheric Corrosion—In indoor exposure of nickel there is practically no attack while outdoors the rate of corrosion varies with atmospheric conditions, being usually at rates less than 0.0001 and never more than 0.001 ipy.* Sulphurous atmospheres are most corrosive. Marine atmospheres are scarcely more corrosive than suburban or rural atmospheres. Nickel is free from season cracking and other forms of stress corrosion in atmospheric exposure.

Waters—Nickel is highly resistant to corrosion by waters such as distilled water,

*Ipy means the depth in inches to which uniform corrosion would penetrate during continuous exposure for one year.

natural waters including those containing hydrogen sulphide or free carbon dioxide, and sea water. In the case of sea water, conditions of agitation or flow are favorable to nickel whereas local attack may occur under barnacles or other attached weeds in stagnant exposure.

Salt Solutions—Nickel resists corrosion by neutral and alkaline salt solutions with rates usually less than 0.005 ipy. Nonoxidizing acid salts are only moderately corrosive with rates seldom over 0.02 ipy. Oxidizing acid salts such as ferric chloride and mixtures of oxidizing salts with mineral acids are likely to be severely corrosive to nickel. This is also the case with oxidizing alkaline salts such as hypochlorites with which nickel should not be used where the available chlorine content exceeds 3 grams per litre. Alkaline solutions containing hydrogen peroxide are not corrosive to nickel and are not decomposed by it.

Mineral Acids—Nickel is fairly resistant to sulphuric acid in concentrations under 80%. Corrosion rates vary from less than 0.005 ipy. in air free to about 0.05 ipy. in air saturated and at atmospheric temperatures. In the presence of oils such as in sulphonation processes, nickel is used successfully with sulphuric acid in concentrations over 80%. Nickel is rarely useful in contact with hot sulphuric acid solutions in concentrations over about 15%.

With hydrochloric (muriatic) acid the rates of attack vary with the air content and concentration of the acid from 0.01 to 0.03 ipy. in dilute acid to 0.06 to 0.25 ipy. in concentrated acid. In hot acid, nickel is rarely useful in handling concentrations over about 2%.

Nickel is not corroded appreciably by chlorinated solvents or mixtures of these with water.

It is resistant to pure phosphoric acid, but is corroded severely by this acid when it contains oxidizing impurities such as ferric compounds.

Sulphurous acid is highly corrosive to nickel except in the case of the very dilute solutions used to preserve foods.

Strongly oxidizing acids, such as nitric, corrode nickel rapidly.

Organic Acids and Compounds—Organic acids are only moderately corrosive to nickel while neutral and alkaline organic compounds have practically no effect.

Alkalies—Nickel is resistant to corrosion by the strongest alkalies. For example, in boiling 50% caustic soda, rates of corrosion are less than 0.001 ipy., and in concentrations over 75%, nickel is second only to silver in resisting attack. Anhydrous ammonia is not corrosive to nickel, but ammonium hydroxide is appreciably corrosive in concentrations over about 1%.

Wet and Dry Gases—No dry gases are actively corrosive to nickel at atmospheric temperature. Nitric oxides, chlorine and other halogens, sulphur dioxide, and ammonia are appreciably corrosive when mixed with water or condensed water vapor. Nickel is resistant to chlorine and hydrogen chloride at temperatures up to about 1000°F.

It is not affected by steam within the range of temperatures and pressures commonly encountered.

Nickel resists scaling in oxidizing atmospheres up to about 1400°F. and is also especially useful in the temperature range from 2100-2300°F.

Nickel is not resistant to mixtures of nitrogen, hydrogen, and ammonia in ammonia synthesis process, but is useful in connection with nitriding equipment when the temperature does not exceed about 1075°F.

At temperatures above 600-700°F., nickel may be attacked by sulphur compounds and gases. Under reducing conditions at temperatures above 1190°F., intergranular sulphur attack will occur. In oxidizing atmospheres, sulphidization increases up to 1800°F., above which temperature it decreases considerably. The addition of about 4% manganese improves the resistance of nickel to sulphur attack.

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Properties of Cast Nickel

By C. A. Crawford*

Nickel castings are available from foundries specializing in the production of high nickel alloys. Small amounts of carbon, silicon, manganese, and a trace of magnesium are intentionally added to yield sound, ductile castings. Sulphur must be kept low. Lead, tin, and zinc should be excluded. The composition of nickel castings is as follows: Ni 97, C 0.25, Si 1.25, Mn 0.50, Fe 0.50, S 0.01 max., Pb nil, 0.1% magnesium is added at the end of the melt.

General Properties and Uses—Nickel castings are used with rolled forms in the fabrication of equipment used in the process industries, such as the manufacture of caustic soda, artificial silk, photographic film, chemicals, pharmaceuticals, dyes, salts, food products, milk, wines, liquors and soap. They are used in valves, pipe fittings, agitator blades, particularly where contamination with copper or iron must be avoided.

Cast nickel is comparable with other forms of nickel in corrosion resistance. It is highly resistant to such corrosives as atmosphere (industrial, marine and rural), fresh water, salt water, neutral and alkaline salts, acid salts and caustic alkalis. Cast nickel is satisfactorily resistant to mineral acids and organic acids. Nickel is not resistant to oxidizing agents, such as nitric acid, ferric chloride, sodium or calcium hypochlorite and wet chlorine.

For more detailed discussion of the corrosion resistant properties of nickel, see the article on Properties of Nickel.

Physical Properties—The physical properties of cast nickel are as follows:

Ultimate tensile strength, psi. (average) ¹	55,000
Yield strength, .3% offset, psi. (average).....	21,000
Elongation, % in 2 in. (average).....	22
Brinell hardness, 10 mm. ball—3000 kg. load.....	120
Rockwell B hardness, $\frac{1}{16}$ in. ball—100 kg. load.....	67
Charpy impact resistance, ft.-lb. (approx.).....	60
Modulus of elasticity (approx.).....	30,000,000
Specific gravity (approx.).....	8.85
Weight per cu. in., lbs. (approx.).....	0.319
Pattern maker's shrinkage, in. per ft.....	$\frac{1}{4}$
Solidification range, °F. (approx.).....	2550-2650
Electrical resistivity ohms/mil ft. at 20°C.....	134
Thermal conductivity at 25°C., cal/cm/cm/sec/°C. (approx.).....	0.14
Coefficient of thermal expansion, per °C. (20-100°C.) (approx.).....	13.3×10^{-6}

¹Tension values determined from $\frac{1}{2}$ in. dia. specimens, separately cast in green sand molds and the test specimens machined therefrom.

Properties of Wrought 62% Nickel-15% Chromium Alloy

By F. E. Bash*

General—This alloy is utilized for its electrical properties and resistance to oxidation at high temperatures. Some of its applications are as follows:

Heat Resistant—Elements for heating devices such as toasters, percolators, waffle irons, flat irons, ironing machines, heater pads, hair driers, permanent waving equipment, hot water heaters; sheet carburizing and annealing containers.

Electrical—High resistance, radio and motion picture rheostats; oxidized wire with high resistance coating for close wound rheostats; potentiometers; thermo-couples.

Corrosion Resistant—Dipping baskets for acid pickling and cyanide hardening; automatic pickling machine parts; filter cloth; enameling racks; containers for molten salts.

Physical and Mechanical Properties

Specific gravity	8.192
Pounds per cu. in.	0.296
Melting point, °F. (approx.)	2462
Specific heat, calories per g.	0.107
Thermal conductivity, calories/cm /sec./°C.	0.0325
Maximum operating temperature, °F.	1700
Electrical resistivity at 20°C. ohms per circular mil. ft.	615
microhm cm.	112
Coefficient of electrical resistivity, 20-100°C. ..	0.0017
68-212°F.	0.00084
Coefficient of linear expansion, 20-100°C. ..	0.000137
20-500°C.	0.00015
20-1000°C.	0.00017
Tensile strength, psi.	175,000 (max.) 95,000 (min.)
Elongation in 2 in., %	35 (max.) 0.5 (min.)
Rockwell hardness	C 24 B 83
Properties at elevated temperatures (loading rate 0.0437 in. min.)	
Temperature, °F	68 392 752 1112 1472 1832
Ultimate tensile, psi.	105,000 97,000 90,000 42,000 25,000 7,100
Elongation in 2 in., %	30 25 16 14 27 45
Reduction in area, %	47 43 29 18.5 40 57

Resistivity—The electrical resistivity of this alloy as given above, is the highest of any of the nickel-chromium-iron compositions. Its resistivity at room temperature depends on the rate of cooling from temperatures in excess of 1000°F. The rapidly cooled material will have a specific resistance of approximately 3% lower than that which has been slowly cooled.

Temperature Coefficient—The temperature coefficient of resistivity is given in Fig. 1. Two curves are shown. These show the increase in resistance with increase in temperature for material annealed in different manners. The maximum is for material which has been quenched and the minimum is for material which has been slowly cooled.

Oxidation Resistance—This alloy, in common with other nickel-chromium and nickel-chromium-iron compositions, develops a tightly adherent coat of oxide, which protects it against further oxidation. This nickel-chromium oxide will flux with silicates such as sodium, potassium and asbestos and oxides (lead and zinc oxides) at high temperatures, which causes oxidation attack on the metal.

The alloy is in general resistant to corrosion where the media are of an oxidizing nature.

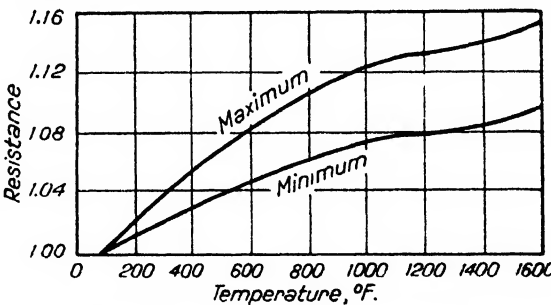


Fig. 1—Temperature resistance curves.

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Properties of the 80% Nickel-20% Chromium Alloy

By W. A. Gatward*

Composition—This alloy is used for high temperature heating elements. The nominal composition is 80% nickel and 20% chromium.

Mechanical and Physical Properties—The following are the properties of the alloy.

Melting point.....	1,400° C., 2,552° F.
Electrical resistivity	
ohms per circular mil ft.....	850
microhms per cm. cube.....	107.9
Tensile strength, psi.....	110,000
Yield point, psi.....	63,000
Elongation, % in 10 in.....	25-35
Reduction in area, %.....	55
Modulus of elasticity.....	31,000,000
Maximum tensile strength obtained by cold work, psi.....	175,000
Temperature coefficient of expansion	
per °F. (70-1,800°F.) average.....	0.0000098
per °C. (70-1,000°C.) average.....	0.0000176
Specific gravity.....	8.4
Pounds per cu. in.....	0.3035
Specific heat.....	0.107
Thermal conductivity watts per sq. cm. per cm. per °C.....	0.136
Hardness, fully annealed Rockwell, B, 100 kg., $\frac{1}{16}$ in. ball.....	85-90
Hardness, hard drawn Rockwell, B, 100 kg., $\frac{1}{16}$ in. ball.....	100-105

Tensile strength at elevated temperatures (quick pull at $\frac{1}{16}$ in. per minute)		Recommended safe loading at elevated temperatures. (The safe loading depends on the permissible creep.)	
Temperature, °F.	psi.		psi.
800.....	98,000.....		26,000-34,000
1,000.....	85,000.....		13,500-21,000
1,200.....	65,000.....		5,300-10,000
1,400.....	30,000.....		1,650-3,500
1,600.....	10,000.....		600-1,300
1,800.....	5,000.....		240-600
2,000.....	3,000.....		100-300

Resistance to Corrosion—Resistance and heating elements of this alloy are not subject to corrosion when used in salt water districts nor when exposed to most fumes and chemicals usually encountered in heating processes. This alloy is susceptible at high temperatures to corrosion by sulphur bearing atmospheres, especially when such atmospheres are reducing.

Temperature vs. Electrical Resistivity—The effect of temperature on the electrical resistivity is not a straight line relation and a coefficient of electrical resistivity may not be applied. Fig. 1 shows the average relation for all sizes of wires. The curve may be used for estimating the hot resistance, but for arriving at an accurate figure in design of heating elements or resistances, an actual test should be made on a complete element under operating conditions.

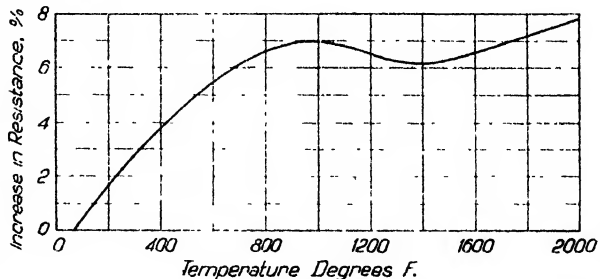


Fig. 1—Temperature vs. resistance for 80% nickel-20% chromium alloy.

Welding—The alloy can be welded by any of the commonly used methods. When oxy-acetylene is used the weld should be made with a slightly reducing flame. A flux of fluorspar is preferable although borax may be used. Welds can be made without flux if the surfaces are not oxidized. If a filler rod is used it should be of the same material. In case a metallic arc method is used the filler rod should be of the coated type developed for this alloy.

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The Properties of Wrought High Nickel-Copper Alloy†

By W. F. Burchfield*

Composition and Physical Constants—Table I gives the composition for this high nickel-copper alloy and the Navy specification, and Table II the physical constants

Table I
Chemical Composition

Element	Typical Composition, %	Navy Specification 46M7 (INT) For Nickel-Copper Alloy Composition, %
Nickel	67.00	63.00-70.00
Copper	30.00	Balance
Iron	1.4	2.5 max.
Aluminum .....	....	0.5 max.
Manganese	1.0	2.0 max.
Carbon	0.15	0.3 max.
Silicon	0.1	0.5 max.
Sulphur .....	....	0.02 max.

Table II
Physical Constants

Density { g. per cu. cm.	8.80
lb. per cu. in.	0.318
Melting point, °F.	2370-2460
Specific heat (20-400°C.)	0.127
Thermal expansion {25-100°C. per °C. ....	.000014
{25-300°C. per °C. ....	.000015
Thermal conductivity (0-100°C.) cgs. units. ....	.06
Electrical resistivity (0°C.) microhm-cm.	42.5
ohms per mil-foot.	256.0
Temperature coefficient of {per °C. ....	.0019
electrical resistivity {per °F. ....	.0011
Modulus of elasticity {Tension, psi.	26,000,000
{Torsion, psi.	9,500,000
Poisson's ratio .....	.32
Magnetic transformation, °F.	80-203

The magnetic transformation point is affected considerably by slight variations in composition and by mechanical and thermal treatment.

Mechanical Properties—Fig. 1 gives the tensile properties of the alloy compared with the Rockwell hardness.

Table III gives the mechanical properties. The ductility of spring wire is sufficient to allow a bend around its own diameter without fracture.

Sheet or strip has a somewhat greater capacity for bending at right angles to the direction of rolling than parallel to the direction of rolling. Results from the Olsen ductility tests are given in Table IV.

Torsional Strength—The torsional values for the alloy in hot rolled and cold drawn condition are given in Table V. In cold drawn rods, hardness gradient makes the measurement of torsional yield strength by the usual method unsatisfactory. Therefore, Johnson's apparent elastic limit is given as being the most useful engineering approximation.

Endurance and Corrosion Fatigue—The endurance limit in the annealed condition, tested in air, is 37,000 psi. When cold worked the endurance limit is as high

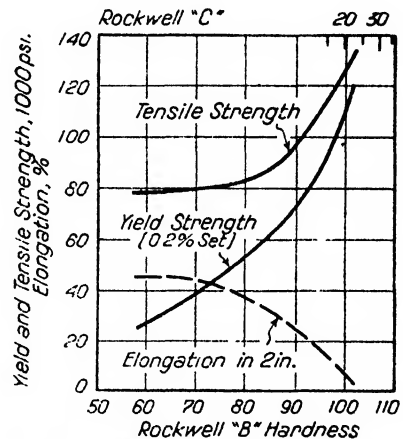


Fig. 1—Average tensile properties of high nickel-copper alloy.

†Trade name "B" Monel.

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Table III
Mechanical Properties

	Tensile Strength, psi.	Yield Strength 0.2% offset, psi.	Proportional Limit, psi.	Elong. in 2 in., %	Izod Impact, ft.-lb.	Brinell Hardness 3,000 kg.
Rod and bar						
Cold drawn and						
Annealed	70,000- 85,000	30,000- 40,000	20,000-30,000	50-35	120- 90	120-160
As drawn	85,000-125,000	60,000- 95,000	45,000-75,000	35-15	115- 75	160-220
Hot rolled	80,000- 95,000	40,000- 65,000	25,000-40,000	45-30	120-100	130-170
Forged	80,000-110,000	40,000- 85,000	25,000-65,000	40-20	115- 75	130-220
Wire, cold drawn and						
Annealed	70,000- 85,000	30,000- 40,000	20,000-30,000	50-35	.....	.....
No. 1 temper	95,000-110,000	65,000- 85,000	.....	10-5	.....	.....
Regular	110,000-140,000	.....	.....	8-4	.....	.....
Spring	140,000-170,000	.....	.....	10-2	.....	.....
Plate, hot rolled						
As rolled	80,000-110,000	40,000- 90,000	.....	45-20	.....	150-220
Annealed	70,000- 85,000	30,000- 45,000	.....	50-30	.....	120-160
						R
						B
Sheet and strip						
Standard sheet	65,000- 80,000	25,000- 35,000	20,000-30,000	40-20	.....	60-68
Special cold rolled						
Annealed	65,000- 80,000	25,000- 35,000	20,000-30,000	40-20	.....	60-68
Full hard sheet	100,000-120,000	90,000-110,000	.....	8-2	.....	98 min
Full hard strip	100,000-130,000	90,000-115,000	.....	15-2	.....	98 min
Tubing, cold drawn						
Annealed	65,000- 85,000	25,000- 35,000	20,000-30,000	35-20	.....	.....
As drawn	90,000-105,000	60,000- 75,000	.....	20-10	.....	.....

Table IV
Olsen Ductility Test on Sheet
(% in. dia. ball, 1% in. dia. die)

Thickness, in.	Condition	Depth to Fracture, in.	Load, lb.
062	{ Annealed	0.560	8,000
	{ Hard	0.315	6,000
.031	{ Annealed	0.500	3,500
	{ Hard	0.225	2,000

Table V
Torsional Strength

	Hot Rolled ¹ , psi.	Cold Drawn, psi.
Breaking strength	61,000-65,000	63,000-85,000
Yield strength	25,000-40,000	.....
Johnson's elastic limit .....	.....	50,000-67,000
Proportional limit	19,000-32,000	45,000-58,000

Table VI
Compression Data

	Compression Yield Strength 0.2% Offset, psi.	Tensile Strength, psi.	Tensile Yield Strength 0.2% Offset, psi.	Elong. in. 2 in., %	Impact Izod, ft.-lb.	Charpy, ft.-lb.	Hardness Brinell Number 3000 kg.	Rock- well "B"
Hot rolled...	38050	83750	40650	39.5	> 120	232	145	82.5
Cold drawn								
as drawn..	80750	97250	86650	27	> 120	151	199	95.5
Annealed ...	26250	78350	33350	44	> 120	206	123	71

as 52,000 psi. This alloy retains a high degree of resistance to fatigue even under corrosive conditions. For example, McAdam found the corrosion fatigue limit in brackish water to be 30,000 psi,* as compared with 8,000 psi. for carbon steel under the same condition.

Toughness—Izod values for hot rolled material range from 100 ft.-lb. to the limits of the 120 ft.-lb. Izod machine. Annealed material has an Izod value of about 90 ft.-lb. and material with as much as 50% cold reduction 65-80 ft.-lb., as shown in Fig. 2.

Compression Strength—Table VI shows compression data with the corresponding tensile, hardness and impact data all obtained from the same rods.

Shear—Table VII contains shear strength values for cold rolled sheet or strip, compared with the tensile strength and Rockwell "B" hardness taken from the same material.

Table VII
Shear Strength of Cold Rolled Sheet or Strip

Temper	Shear Strength, psi.	Tensile Strength, psi.	Rockwell "B" Hardness
Annealed..	49,200	70,000	61
Full Hard.	65,200	116,000	100

Hardness—The mechanical properties and hardness of this nickel-copper alloy are increased only by cold working. It does not respond to hardening by heat treatment.

Fig. 3 shows the work hardening by various percentages of cold reduction obtained by cold rolling strip, as compared with other commercial metals and alloys.

To give various balances between ductility, strength and hardness, cold rolled sheet and strip are furnished in nine different hardness ranges, as shown in Table VIII.

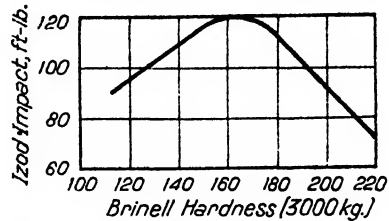


Fig. 2—Relationship between impact and surface hardness.

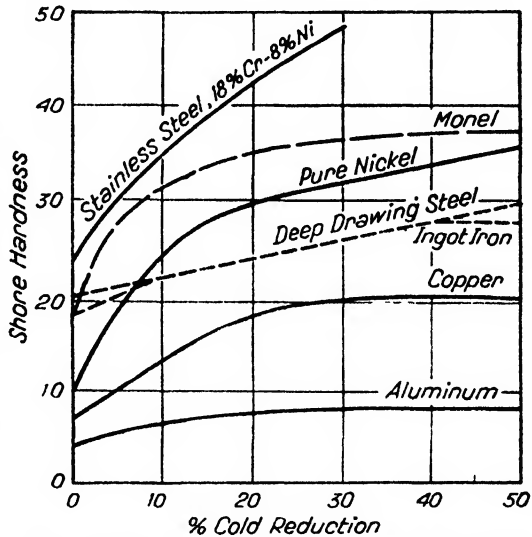


Fig. 3—Work hardening by various percentages of cold reduction.

Table VIII
Hardness of Cold Rolled Sheet and Strip

	Sheet		Strip	
	Shore	Rockwell B	Shore	Rockwell B
Dead soft	16 & under	60 & under	16 & under	60 & under
Soft	17-20	61-73	17-18	61-68
Soft-skin hard	19-20	74-82	19-20	69-73
Skin hard	21-24	83-89	21-24	74-82
Quarter hard	25-30	90-93	25-30	83-89
Half hard	31-35	94-97	31-35	90-93
Three-quarter hard	36-40	Over 97	36-40	94-97
Hard	Over 40	Over 97	Over 40	Over 97
Full hard				

Elastic Moduli—Young's modulus of elasticity is 26,000,000 and the torsional modulus is 9,500,000. Variation of moduli with cold worked or hot worked condition is not great enough to be significant. The moduli decrease with an increase in temperature. From room temperature to about 400°F., the decrease is about 1,000,000.

Elevated Temperatures—The data in Table IX are for annealed, hot rolled rod and indicate the change of tensile strength and yield strength as determined by short time tests at various temperatures. Table X gives creep test values on annealed, hot rolled rod.

Table IX
Short Time, High Temperature Properties of Hot Rolled Bars

Temp., °F.	Tensile Strength, psi.	Yield Strength 0.2% Offset, psi.	Elong in 2 In., %
70	84,925	32,900	45.8
800	79,625	26,500	49.5
800	69,085	25,375	51.0
1000	50,450	23,925	27.3
1200	32,050	18,360	32.8
1500	14,575	8,375	49.0

Table X
Creep Value^a

Temp., °F.	Stress to Produce Designated Rate of Creep psi.		
	Rate of Creep 0.01% per 1000 hr.	Rate of Creep 0.1% per 1000 hr.	Rate of Creep 1.00% per 1000 hr.
600	26,000	36,000	46,000
800	19,000	23,500	29,000
1000	1,650	4,300	11,500
1200	.....	.....	1,700

Recrystallization Temperatures—While there is evidence that recrystallization of previously highly stressed high nickel-copper alloy may begin at 800°F., no actual annealing can be expected at temperatures below 1200°F., and even at this temperature the annealing time is too slow to be commercially useful. The greater the amount of previous cold work, the lower will be the recrystallization temperature.

Low Temperatures—The proof stress, yield strength, tensile strength, and hardness of this material, all increase as the temperature is lowered. In spite of the increase in yield strength and tensile strength, the alloy suffers no loss in ductility or impact value.

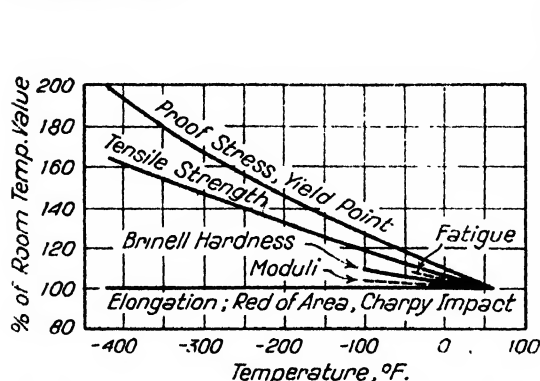


Fig. 4—Percentage change in properties for high nickel-copper alloys at low temperatures.

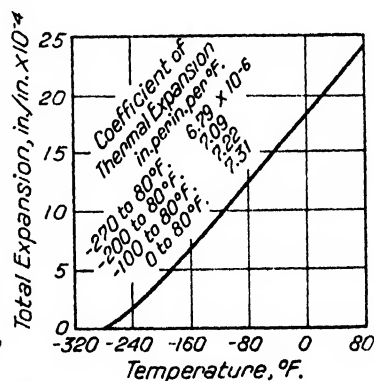


Fig. 5—Coefficient of thermal expansion of the high nickel-copper alloy.

Fig. 4 shows the percentage of change of the important physical properties as the temperature drops to that of liquid air. **Fig. 5** shows the coefficient of thermal expansion increases slightly with decrease in temperature for the annealed alloy.

Corrosion Resistance—This alloy is a simple, solid solution alloy, so is free from such types of corrosion as sometimes result from local galvanic effects between phases of multiphase alloys.

The types of corrosive discussed below apply to this alloy as well as special grades of it.

Atmospheric Corrosion—In indoor atmospheres this alloy remains substantially unchanged, the principal effect being a slow fogging. In outdoor atmospheres it remains bright only in rural districts that are free from sulphur gases. In sulphurous atmospheres, it will acquire a brownish or greenish tarnish at a rate which will depend on the sulphur content and humidity of the atmosphere. Even where the rate of tarnishing is greatest, there is no destructive corrosion of the metal as it is free from internal structure weakness, season cracking, or stress corrosion cracking. Weight loss data from atmospheric corrosion test specimens have indicated rates of corrosion of less than 0.0001 in. penetration per year at all test locations.

Fresh Water—This high nickel-copper alloy possesses excellent resistance to corrosion by distilled water and natural water, both hard and soft. In distilled and fresh water, rates of corrosion are less than 0.001 in. penetration per year, and often less than 0.00001 in. under the most severe conditions of temperature, flow, and degree of aeration.

Salt Water—This material finds its greatest usefulness in sea water under conditions involving contact with water at high velocity. Stagnant sea water is less favorable, since local attack may occur under marine organisms or other deposited solids.

Neutral and Alkaline Salts—Neutral and alkaline salts have only a slight corrosive action. Rates of corrosion are usually less than 0.001 and seldom more than 0.005 in. penetration per year. It is highly resistant to sodium and calcium chlorides as used in refrigerating brines.

Acid Salts—The material shows good resistance to acid salt solutions, such as zinc chloride, ammonium sulphate, aluminum sulphate, aluminum chloride, and ammonium chloride.

Oxidizing Acid Salts—It is not highly resistant to most oxidizing acid salts, such as ferric chloride, ferric sulphate, cupric chloride, stannic chloride, mercuric chloride, and silver nitrate. This applies also to acids containing chromates, dichromates and other oxidizing compounds.

Oxidizing Alkaline Salts—Hypochlorites are the only common alkaline salts that are definitely corrosive to this alloy. The limiting concentration of available chlorine that may be handled safely is 3 grams per litre. This material is unaffected by alkaline peroxide bleaching solutions.

Mineral Acids—Good resistance to corrosion is shown by all acids except those of a highly oxidizing character. In nonoxidizing acids corrosion does not proceed in the absence of dissolved oxygen.

In air free sulphuric acid at atmospheric temperature, corrosion of the alloy is practically nil in all concentrations up to about 80%. In air saturated acid, below 80% concentration, maximum corrosion occurs with 5% acid at a rate of about 0.04 in. penetration per year.

In 5% acid saturated with air, the most active temperature is about 185°F. The rate of corrosion is about 0.12 in. penetration per year.

The material may be used successfully for handling boiling sulphuric acid (220°F.) solutions in concentrations up to 20%.

In hydrochloric acid the corrosion increases directly with acid concentration. In cold, air free acid, rates of corrosion range from about 0.005 in 1% acid to about 0.04 in. penetration per year in 30% acid. In cold, air saturated acid the spread in corrosion rates is from about 0.03 in 1% acid to 0.2 in. penetration per year in 30% acid. At temperatures in excess of 120°F. the practical application is confined ordinarily to concentrations of hydrochloric acid under 2%.

This alloy is practically unaffected by hydrofluoric acid and mixtures of hydrofluoric acid and fluorides throughout a wide range of concentration and temperature.

The resistance to phosphoric acid depends principally on the purity of the acid, especially in regard to the presence of such oxidizing impurities as ferric compounds.

This alloy is corroded at a moderate rate by hydrogen sulphide with the formation of a dark tarnish, but gives useful resistance to corrosion by oil well brines containing hydrogen sulphide.

Oxidizing Acids—In nitric acid the safe conditions of use include concentrations under 1% at temperatures under 80°F. and where there is little or no movement of the solution or the metal.

Sulphurous acid and bisulphites may be appreciably corrosive.

Organic Acids and Compounds—The alloy shows good resistance to corrosion by all the common organic acids, and is practically free from corrosion by neutral and alkaline organic compounds, and fruit and other food acids.

Alkalies—This alloy is practically resistant to most alkaline solutions, including concentrated caustic soda solutions at temperatures up to the boiling point. In aqua ammonia, or ammonium hydroxide solutions, the material may be used successfully at concentrations up to 3% NH₃. It is not corroded by anhydrous ammonia.

Wet and Dry Gases—This alloy is corroded appreciably by such gases as chlorine, bromine, sulphur dioxide, nitric oxide, and ammonia in the presence of water or condensed water vapor. It is usefully resistant to the effects of steam through the common operating ranges of temperature and pressure.

It is attacked by mixtures of nitrogen and hydrogen under the conditions encountered in ammonia synthesis.

It may be used without progressive scaling at temperatures up to at least 1000°F.

Hot Working Properties—This alloy requires more power for forging than mild steel. It should be placed in a hot furnace and forging started when the temperature is reached. It should not be held at the forging temperature. Sulphur-free fuel should be used or low sulphur content fuel used with precautions. The combustion of the fuel should be complete before the hot gases strike the metal.

The recommended range of forging temperatures is 2150-1600°F. All heavy forgings should be forged above 1850°F. The hot bending range is 2150-1850°F. Care should be taken not to heat the material above the upper recommended temperature limit.

This high nickel-copper alloy may exhibit red shortness within the temperature range of 1200-1600°F.

Cold Working—The high nickel-copper alloy behaves similarly to mild steel in mechanical cold working, as in cupping, drawing, swaging, die forging, power hammering, bending, and forming. The elastic limit is higher, hence more power is required.

Deep Drawing—The deep drawing practice closely follows that for steel. Lubricants with high film strength, such as tallow, castor oil, or good soluble drawing compounds, should be used. Lubricants containing sulphur or lead should not be used if annealing is necessary. The pieces should be annealed after 35-50% reduction.

Spinning—For spinning, the metal should be laid down on hard chucks using long, powerful strokes. Use roller tools if available. Hand tools should be of hardened high speed steel or hard bronze. Tallow or yellow laundry soap should be used for a lubricant. The work must be annealed frequently and in all cases before the ductility of the metal has been exhausted.

Annealing—Bright annealing is easily accomplished in both box and open annealing. Boxes are carefully luted and gas is admitted during the cooling cycle to prevent the entrance of air. In open annealing, sulphur-free oil should be used in furnaces designed so that combustion takes place before the gases strike the work. A reducing sulphur-free atmosphere is essential. An alcohol quenching bath, in the proportion of 1 gal. of methyl or denatured ethyl alcohol to 50 gal. of water, will reduce the oxide flash that results when the work is brought out into the air and will give a silvery white surface. A pink color after the alcohol quenching indicates oxidation in the furnace and improper heating conditions, or an undue delay in quenching.

Lubricants and other foreign matter should be removed thoroughly before annealing.

Table XI gives the recommended annealing temperatures and time at temperature for open and box annealing.

Table XI
Time and Temperature for Annealing

	Temperature, °F.	Time at Temperature
Open Annealing.....	1600-1650	10-7.5 min.
	1700-1750	5-2 min.
	1800	½ min.
Box Annealing...	1350-1450	2-6 hr.

Machining—For details on machining of high nickel alloys, see page 1679.

Welding—For details on welding, see page 220.

Pickling—In commercial pickling, the oxide is first reduced by heating and cooling in a definitely reducing atmosphere, as described under Annealing. A suitable solution for removing the adherent reduced metal is:

Water	3 qt.
Sulphuric acid (66°Baumé)	30½ oz.
Sodium nitrate (crude)	12 oz.
Sodium chloride	12 oz.

Add the acid to the water, then dissolve the sodium nitrate, then add more water to make 1 gal. The temperature should be 180-190°F. and the time required will be 20-30 min., after which the loosened scale may be removed completely by hand or mechanical scrubbing.

In cases where it is impractical to reduce the oxide, its removal may be accomplished in the following pickling solution:

Water	2 gal.
Hydrochloric (muriatic) acid	1 gal.
Cupric chloride (copper chloride)	½ lb.

Cupric chloride speeds up the pickling, but it may be omitted if not available. The temperature should be 180-190°F. The time required, if cupric chloride be used, will be 20-40 min. The articles should be removed at frequent intervals and scrubbed with pumice stone or fine sand, and returned to the pickling solution. Tarnish remaining after the pickling, is removed in a second solution made up as follows:

Water	1 gal.
Sulphuric acid (66°Baumé)	0.1 gal. (1.5 lb.)
Sodium dichromate	1.1 lb.

The temperature should be 70-100°F. and the time required will be 5-10 min., after which the articles should be rinsed in cold water and then dipped in a dilute solution of ammonia (2½ oz. per gal. of 26°Baumé ammonia).

For bright dipping, clean the work in a solution of: water, 1 gal.; nitric acid (38°Baumé) 1 gal.; common salt, 0.8-1.2 oz. Then rinse in hot water and dip quickly for not over 5 seconds in a solution of: water, 1 gal.; nitric acid (38°Baumé), 1 gal. Rinse and dip in the ammonia solution used for pickling. Dry by dipping in steaming water or by rubbing with sawdust. These solutions for bright dipping are used at room temperature.

Forms Available—This alloy is available in the usual mill forms such as hot rolled plates, sheet and strip, rods, shapes, tubing and pipe, wire, and as forgings, castings.

References

- ¹P. D. Merica, R. G. Waltenberg, and A. S. McCabe, Some Mechanical Properties of Hot Rolled Monel Metal, *Proc., A.S.T.M.*, 1921, v. 21, p. 922.
- ²D. J. McAdam, Corrosion-Fatigue of Non-ferrous Metals, *Proc., A.S.T.M.*, 1927, v. 27, pt. II, p. 122.
- ³C. L. Clark and A. E. White, Symposium on Effect of Temperature on Metals, *A.S.T.M.-A.S.M.E.*, 1931, p. 383.

Properties of Wrought Special High Nickel-Copper Alloy† (Machining Quality)

By W. F. Burchfield*

The composition of this nickel-copper alloy and the Navy specification are given in Table I.

Table I
Composition of Nickel-Copper Alloy

Elements	Typical Composition, %	Navy Specification 46M7 (INT) For Nickel-Copper Alloy (Free Machining) Composition, %
Nickel	67.00	65.00-70.00
Copper	30.00	Balance
Iron	1.7	2.5 max.
Aluminum .....	....	0.5 max.
Manganese	1.1	2.0 max.
Carbon	0.1	0.3 max.
Silicon	0.05	0.5 max.
Sulphur	0.035	0.025-0.060

This alloy is produced as cold drawn or hot rolled rods for automatic screw machines where high cutting speeds must be maintained. Free machining qualities are obtained with a sacrifice in toughness and strength. The composition has good ductility at room temperatures, but is hot short over a wide range of temperatures so cannot be subjected to hot heading or forging operations.

The physical constants are practically the same as those shown on page 1655. The mechanical properties are given in Table II.

Table II
Range of Mechanical Property

	Tensile Strength, psi.	Yield Strength 0.2% Set, psi.	Elong. in 2 in., %	Rockwell B Hardness ½ in. Ball, 100 kg.
Hot rolled				
½-1 in. dia.	80- 95,000	40-65,000	45-30	70-85
1-2 in. dia.	80- 95,000	35-65,000	40-30	60-85
2-3 in. dia.	75- 85,000	35-60,000	40-30	60-85
Hot rolled squares, hexagons, flats				
All sizes	75- 90,000	35-65,000	45-30	60-85
Cold drawn				
½-½ in. dia.	100-115,000	75-90,000	10-5	90-100
½-1½ in. dia.	90-100,000	70-90,000	35-15	85-100
1½-2 in. dia.	85-100,000	65-90,000	35-15	80-95
2-3 in. dia.	80- 95,000	60-85,000	35-20	75-85
Cold drawn squares, hexagons, flats				
All sizes	80- 95,000	50-75,000	35-25	80-90

*Development & Research Division, International Nickel Co., New York

†Trade name "R" Monel.

Properties of Cast High Nickel-Copper Alloy†

By C. A. Crawford*

Composition—The composition of this cast alloy controls the limits of the minor constituents, such as silicon, manganese, carbon, iron and magnesium, and excludes the metals which have a detrimental effect on the physical properties at room and steam temperatures, notably lead. Zinc and tin are excluded from this composition for casting, but tin is used in special nickel-copper-tin alloys of high nickel content. Sulphur should be kept to the lowest possible minimum. Magnesium must be used as a desulphurizer and will be found in small amounts. The approximate composition is as follows: nickel 67%, copper 29%, iron 1.50%, silicon 1.25%, manganese 0.90%, carbon 0.20%, sulphur 0.015% max., and lead nil.

The specifications covering this alloy are the Federal specification QQC-551 and the United States Navy 46M1, both for sand castings.

General Properties and Uses—The castings of this alloy show good resistance to corrosion by many mineral acids and salt solutions. They have high strength at the temperatures of saturated and moderately superheated steam (up to 800°F.) and show good resistance to erosion by wet steam.

The castings are used for pump parts, valve bodies, valve trim and turbine nozzles for water, steam and chemical process service. They are used as fittings in pipe lines, pump liners, laundry and textile machine parts, agitators, conveyor chain, flanges, drains, ejectors, gears, heater jets, nuts, manifolds, nozzles, reels, scrapers, screw conveyors, spiders, spouts, strainers, tank fittings, tie rod clamps, and similar applications.

The physical properties are given in Table I.

Table I
Physical Properties High Nickel-Copper Alloy Castings

Ultimate tensile strength, psi. (average ¹)	70,000
Yield strength, .2% offset, psi. (average)	35,000
Elongation, % in 2 in. (average)	30
Brinell hardness, 10 mm. ball—3000 kg. load	140
Rockwell B hardness, 1/16 in. ball—100 kg. load	75
Charpy impact resistance, ft.-lb. (approx.)	70
Modulus of elasticity (approx.)	26,000,000
Specific gravity (approx.)	8.80
Weight per cu. in., lb. (approx.)	0.318
Pattern maker's shrinkage, in. per ft.	1/4
Solidification range, °F.	2,400-2,500
Electrical resistivity, ohms mil ft. 25°C.	323
Thermal conductivity at 25°C., cal/cm/cm/sec/°C. (approx.)	0.05
Coefficient of thermal expansion, per °C. {20-100°C.} (approx.)	13. × 10 ⁻⁶
	{20-455°C.} " 15.8 × 10 ⁻⁶

*Tension values determined from 1/2 in. dia. specimens, separately cast in green sand molds and the test specimens machined therefrom.

*Development and Research Division, International Nickel Co., New York

†Trade name Monel.

Properties of Wrought Nickel-Manganese Alloys

By W. A. Mudge*

General—The nickel-manganese alloys belong essentially to the specialty class of engineering materials. They have good mechanical properties and possess a considerable resistance to corrosion toward most media, comparable to that of pure nickel. The presence of manganese in nickel reduces the susceptibility to attack by sulphur gases and accounts for the use of the alloys where this factor is of particular importance.

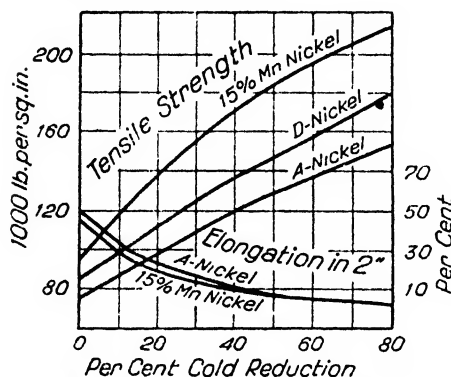


Fig. 1—The effect of cold drawing upon the tensile strength and elongation (in 2 in.) of nickel-manganese alloys.

given in Table IV.¹ The 15% manganese-nickel alloy has a specific resistance of 290 ohms per mil-ft. (48.19 microms per cm.), a maximum permeability of 8400 gausses at $H = 0.05$, as compared to 5000 at $H = 0.37$ for grade "A" nickel.² The saturation and transformation temperatures are lowered by manganese, the latter effect being about 33°F. per per cent of manganese.³ Alloys containing more than 20% of manganese have limited hot malleability and are not commercial.

Annealing Treatment—The temperatures for annealing are 1300-1400°F., the higher temperature corresponding to the higher percentage of manganese. Cooling from this temperature may be either slow or rapid as the alloys cannot be hardened by heat treatment.

Wrought Forms—The alloys are produced in the usual wrought forms, such as hot rolled or cold drawn rods, bars, wire, and special shapes. Sheet, strip, and plate can be made if desired. Tubing is not available.

Uses—The principal uses of these alloys are for spark plugs, ignition tubes, dental wires, electrical resistance wires, enameling points.

The most important commercial alloys are those containing 2, 5, and 15% manganese, respectively.

Chemical Composition—The figures in Table I are typical of the chemical analyses. Similar values for pure nickel (grade "A" nickel) are included for comparison.

Mechanical Properties—The tensile and torsional properties of 1 in. dia. hot rolled rods¹ are given in Tables II and III. Fig. 1 shows the effect of cold work upon the strength and ductility of the alloys in wire form.

Other Properties—The alloys are similar to pure nickel in general appearance. Each per cent of manganese reduces the density of nickel (8.88 g. per cc.) by about 0.02 and the melting point (1455°C.) by about 5°C. Some electrical properties of these alloys are

Table I

Chemical Composition

Material	C	S	Si	Cu	Fe	Mn	Ni
Grade "A" nickel.....	0.10	0.005	0.07	0.05	0.20	0.15	99.40
Grade "E" nickel.....	0.10	0.005	0.10	0.10	0.20	2.00	97.50
Grade "D" nickel.....	0.10	0.005	0.10	0.10	0.20	4.65	94.80
15% Mn-nickel	0.12	0.005	0.20	0.10	0.25	15.00	84.30

*Metallurgist, Huntington Works, The International Nickel Co., Inc., Huntington, W. Va.

Table II
Tensile Properties and Hardness of 1 In. Dia. Hot Rolled Rods

Material	Yield Point, psi.	Breaking Strength, psi.	% Elonga- tion in 2 in.	Reduction of Area	Rockwell B Hardness	Brinell Hardness 3000 kg.
Grade "A" nickel.....	30,000	77,000	45.0	68.0	60	133
Grade "E" nickel.....	32,000	81,000	45.0	65.0	64	140
Grade "D" nickel.....	34,000	86,000	40.0	60.0	70	147
15% Mn-nickel.....	38,000	95,000	38.0	60.0	75	155

Table III
Torsional Properties of Hot Rolled Rods, 1 In. Dia.

Material	Yield Point, psi.	Breaking Strength, psi.	Angle of Twist, ° per in.	Shear, in per in.	Ratio Breaking Strength in Shear to Breaking Strength in Tension
Grade "A" nickel.....	35,000	65,000	400	3.05	0.84
Grade "E" nickel.....	28,500	66,000	390	2.90	0.82
Grade "D" nickel.....	26,000	68,000	380	2.70	0.79
15% Mn-nickel	27,000	71,000	460	3.95	0.75

Table IV
Electrical Properties

Material	Ohms per mil-ft.	Michroms per cm ²	Temp. Coefficient— 20-100°C.	20-1000°C.	Thermal emf. vs. Platinum at 1800°F.
Grade "A" nickel.....	60	9.97	0.0045	0.0036	— 8.19
Grade "E" nickel.....	85	13.95	0.0042	0.0032	— 3.84
Grade "D" nickel.....	120	19.95	0.0036	0.0024	— 4.64

References

- ¹W. A. Mudge and L. W. Luff, Some Mechanical Properties of Nickel, Manganese-Nickel, and Copper-Nickel Alloys, Proc., A.S.T.M., 1928, v. 28, pt. 2, p. 278-291.
- ²Driver-Harris Co., Data and Specifications Pertaining to Alloys for Electrical Resistance, p. 43.
- ³C. Bleber, International Nickel Co.

Properties of Wrought Nickel-Copper-Aluminum Alloy*

By C. A. Crawford*

Composition and Physical Constants—The following composition and physical constants are typical of the nickel-copper-aluminum alloy known as "K" monel.

Typical Composition	%	Specification Limits, %
Nickel	66.00	63.00 min.; 70 max.
Copper	29.00	Remainder
Aluminum	2.75	2.00 min.; 4.00 max
Iron	0.90	2.00 max.
Manganese	0.40	1.00 max.
Carbon	0.15	0.25 max.
Silicon	0.25	0.50 max.
Sulphur	0.005	.....
Other metals .....	.....	1.00 max.

Physical Constants

Specific gravity.....	8.60
Weight, lb. per cu. in.....	0.31
Melting point, °F.....	2400-2460 (1315-1350°C.)
Specific heat (20-400°C).....	0.127
Thermal expansion (average coefficients):	
(25-100°C.) .....	.000014
(25-300°C.) .....	.000015
(25-800°C.) .....	.000016
Heat conductivity (0-100°C.), cgs.....	.043
Electrical resistivity (at 23°C.):	
Hot rolled or forged and quenched, microhm centimeters....	62.8
Hot rolled or forged and quenched, ohm per mil-foot.....	378.
Heat treated, microhm centimeters.....	62.0
Heat treated, ohm per mil-foot.....	373.
Temperature coefficient of electrical resistivity, per °C. (23-100°C.).....	.00019
Magnetic transformation temperature.....	below -79°C.
Modulus of elasticity in tension.....	28,000,000
Modulus of elasticity in torsion.....	9,500,000

Strength in Double Shear—The double shear strength measurements given below were made with the cutters set with a small clearance (.005 in.). This type of test stimulates the service requirements of pins used in shackles or clevises.

Tension		Double Shear	
Tensile Strength psi.	Elongation, % in 2 in.	Maximum Strength, psi.	Deflection at Max. Strength in inches
97,500	49.0	65,300	0.08
155,600	24.0	98,700	0.05

Mechanical Properties—The mechanical properties are given in Tables I and II.

Spring Properties—Wire can be drawn and heat treated from this alloy to 170,000-200,000 psi. tensile strength. The torsional proportional limit cold drawn and heat treated is about 80,000 psi.

This alloy can be used when springs in large sizes cannot be fabricated wholly by cold process. The springs can be made from soft rod or formed hot and the spring temper developed by heat treatment. In this case the tensile proportional limit and tensile strength will be at least 80,000 and 140,000 psi., respectively, and may be greater depending upon the size of the spring and the amount of cold work developed by the coiling.

Endurance Limit—Measurements of endurance limit in air for rod made on a rotating cantilever fatigue testing machine are given in Table III.

Impact—The impact resistance decreases with increasing hardness. Impact values are given in Table IV.

*The trade name of this alloy is "K" Monel.

*Development and Research Division, International Nickel Co., New York.

Table I
Mechanical Property Ranges

Form and Temper	Tensile Strength, psi.	Yield Strength (0.2% Offset), psi	Elongation in 2 in., %	Brinell Hardness (3000 kg.)	Rockwell C Hardness
Rods and Bars					
Cold Drawn					
Annealed	90-110,000	50-70,000	45-35	140-180	75-90†
Annealed—heat treated	130-150,000	90-110,000	30-20	240-260	21-25
As drawn	100-125,000	70-100,000	35-20	175-250	8-23
As drawn—heat treated	140-170,000	100-130,000	30-15	260-320	25-33
Hot Rolled					
As rolled	90-110,000	40-60,000	45-35	140-180	75-90†
As rolled—heat treated	135-160,000	100-120,000	30-20	260-300	25-31
Forged					
As forged	90-115,000	50-75,000	40-30	140-200	75-95†
As forged—heat treated	135-165,000	100-125,000	30-20	260-310	25-32
Wire, Cold Drawn					
Annealed	90-110,000	50-70,000	45-35	.....	.....
Annealed—heat treated	130-150,000	90-110,000	30-15	.....	.....
Spring temper	145-175,000	.....	4-2	.....	.....
Spring temper—heat treated ..	170-200,000	.....	8-3	.....	.....
Strip, Cold Rolled					
Soft	90-105,000	50-65,000	45-30	.....	75-85†
Soft—heat treated	130-150,000	90-110,000	25-10	.....	20-30
½ hard	125-145,000	85-105,000	20-10	.....	15-23
½ hard—heat treated	150-180,000	110-130,000	15-5	.....	23-35
Full hard	145-165,000	105-120,000	8-2	.....	25-32
Full hard—heat treated	170-200,000	125-145,000	10-2	.....	33-40

†Rockwell B Scale.

Table II
Mechanical Properties—Strip

Condition (a)	Tensile Strength, psi.	Yield Strength (c), psi.	Elong. % in 2 in.	Scleroscope Hardness	Hardness Rockwell C Scale
Cold rolled, soft	105,000 max.	.....	25.0 min.	23 max.	8 max.
Cold rolled, soft—heat treated	130,000 min.	90,000 min.	10.0 min.	35 min.	20 min.
Cold rolled, half hard(*)	125,000 min.	85,000 min.	5.0 min.	30 min.	15 min.
Cold rolled, half hard—heat treated ..	150,000 min.	110,000 min.	3.0 min.	45 min.	28 min.
Cold rolled, full hard(b)	145,000 min.	105,000 min.	3.0 min.	40 min.	25 min.
Cold rolled, full hard—heat treated ..	170,000 min.	125,000 min.	2.0 min.	50 min.	33 min.

(a) Approx. 20% reduction.
 (b) Approx. 50% reduction.
 (c) By drop of beam or dividers.
 (d) No tensile requirements under .020 in. thick; substitute shore scleroscope hardness.

Table III
Limiting Stress in Fatigue

Brinell Hardness No.	Tensile Strength, psi.	Yield Strength .01% Offset, psi.	Million Cycles in Test	Limiting Stress, psi.
145	90,000	26,000	70	38,000
170	106,000	63,000	20	45,000
235	142,000	101,000	30	50,000
330	158,000	105,000	20	52,000

Table IV
Impact Values

Condition	Tensile Strength, psi.	Standard Izod Test, ft.-lb.
Hot rolled	100,000	120+
Cold drawn	106,000	56
Hot rolled heat treated	151,000	40
Cold drawn heat treated	158,000	26

Magnetic Characteristics—This alloy is nonmagnetic under ordinary working conditions and remains so at subnormal temperatures. Careful measurements of permeability at field strengths from 10-300 gilberts per centimeter has shown the permeability (B/H) at room temperature to be 1.0, the same as air. No measurable difference in magnetic permeability between the soft and fully hardened alloy has been found at temperatures higher than -79°C .

Hot Working—When heating, the flame should not impinge directly on the metal. The fuel should be free from sulphur and a reducing atmosphere maintained.

The furnace may be operated at $2200\text{--}2250^{\circ}\text{F}$. However, the metal should never be allowed to reach this figure, but should be removed on a rising temperature between $2000\text{--}2175^{\circ}\text{F}$. This alloy should not be placed in a cold furnace and brought up to temperature, but should be charged into the hot furnace.

The hot working operation must be stopped when the temperature falls to 1700°F . and if the hot work is not completed, the pieces should be immediately returned to the furnace and reheated to the forging temperature. If the continuation of the hot work is not to follow immediately, the work should be held until the temperature drops to 1450°F . and then immediately quenched in water to which 2% alcohol by volume has been added. Unless this quenching is done, stresses will be set up that may result in surface tears on reheating. This alloy air cooled from 1700°F . and not quenched will be excessively hard for practical cold forming or working later.

Cold Working—The increase in tensile strength with cold work is shown in Fig. 1.

Rod—As cold drawn, the tensile strength will be 100,000-135,000 psi. For strength above 135,000 psi, the material must be heat treated.

Strip—The hardness of strip as cold rolled full hard, will be 25-32 Rockwell C and a tensile strength of 165,000 psi.

Wire—Spring wire as cold drawn (65% reduction) and stress-relief annealed at 525°F . will have a tensile strength of 145,000-175,000 psi.

Softening by Quenching—This treatment is carried out at the mill after cold rolling, forging, or cold drawing and should not be

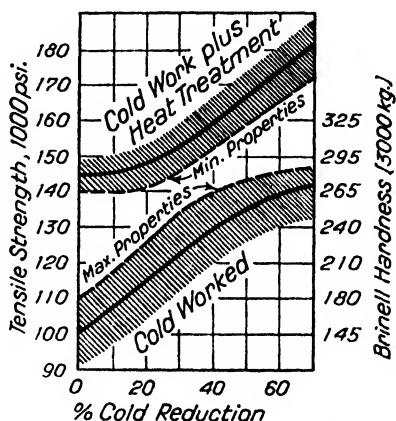


Fig. 1—Effect of cold work and heat treatment

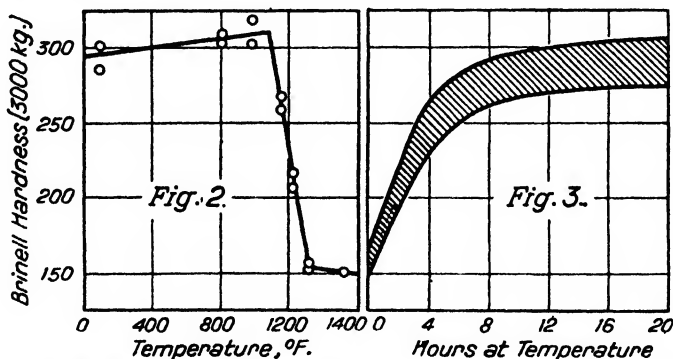


Fig. 2—Softening by quenching from various temperatures.

Fig. 3—Hardening by increasing the holding time.

repeated before the hardening treatment. If it is desired to soften for machining or for cold working proceed as follows:

Heat to a temperature between $1400\text{--}1450^{\circ}\text{F}$., and quench in water or oil. The alloy will not soften if cooled in air except in sections $\frac{1}{4}$ in. dia. or less. Open heating in a sulphur free reducing atmosphere is preferred to using a box because

of the greater ease of quenching. Water to which 1-2% by volume of denatured alcohol has been added is most commonly used as the quenching medium. The alcohol will partially reduce the film of oxide on the metal.

Hardening by Heat Treatment—Hardening by heat treatment is done by holding the metal for 10-16 hr. at 1080-1100°F. followed by slow cooling in the furnace. Fig. 3 shows how hardness increases with holding time.

Higher hardnesses are obtained by cold working (20-30% reduction) then holding for at least 6 hr. at 1080-1100°F. (980-1000°F. for 50% reduction or over), cool to 800°F. at a controlled rate of 25°F. per hr. Cool from 800°F. in any convenient manner.

When the metal has not been cold worked after quenching it may be hardened by holding 30-60 min. at 1200-1250°F. followed by cooling to 800°F. at a rate of 25°F. per hr.

Long Time Aging

Treatment	Tensile Strength, psi.	Yield Strength (0.2% Offset), psi.	Elong. % in 2 in.	Reduction in Area, %	Izod Impact, ft.-lb.	Hardness Vickers 30p
As hot rolled.....	97,500	40,500	44.0	60	83	180
16 hr. at 1080°F.....	147,000	92,000	28.0	44	48	298
16 hr. at 1080°F. followed by 1 month at 800°F.....	161,500	109,000	28.0	40	26	359
16 hr. at 1080°F. followed by 2 months at 800°F.....	165,000	112,000	25.0	40	23	353
16 hr. at 1080°F. followed by 4 months at 800°F.....	162,300	109,200	25.5	41	24	359
16 hr. at 1080°F. followed by 8 months at 800°F.....	164,300	113,200	23.1	37	27	355
16 hr. at 1080°F. followed by 16 months at 800°F.....	163,500	112,000	24.5	37	25	348

Machining—This alloy with a 300 Brinell hardness can be machined. See page 1679 for the machining of nickel alloys.

Welding—For details on welding see the article on page 220.

Grinding—When grinding it is important to avoid excessive heating, which will change the hardness. Grinding should be done under water or coolant whenever possible.

Pickling—The pickling procedure on page 1661 is suitable for this alloy.

Corrosion Resistance—The corrosion resistance is comparable to that of Monel in organic acids, alkalis, salts, industrial waters, food products, organic compounds and atmospheric oxidation at normal and elevated temperatures; and is superior in aerated ammonia solutions, and inferior in hot dilute sulphuric acid.

Properties of Cast High Nickel-Copper-Silicon Alloys^{a,b}

By C. A. Crawford*

Composition—The 3% silicon, high nickel-copper alloy has good strength and ductility while the 4% silicon type has higher hardness plus resistance to galling but the ductility is low. The composition is as follows:

Ni	Cu	Si	Fe	Mn	C	S max.	Pb
65.0	29.5	3.0 ^a	1.5	0.5	0.1	0.015	Nil
63.0	30.0	4.0 ^b	2.0	0.5	0.1	0.015	Nil

The 4% silicon type has a hard matrix and a structure of fine silicides.

Machining—High speed steel tools are employed for machining the 3% silicon type, but carbide tools are more suitable for the 4% silicon alloy.

Heat Treatment—These alloys are annealed by heating to 1600°F., air cooled to 1200°F., and quenched in oil. The finished work may then be rehardened by heating at 1100°F. for four hours, furnace or air cool.

Hardness—The Brinell hardness of the 4% silicon type in the as cast condition is 330 with 3000 kg. load, 10 mm. ball; after annealing it is 240 and after rehardening 360.

Properties and Uses—The 3% silicon type is used for cast turbine nozzles and steam outlets or in rotating parts where the stresses are high. The 4% silicon alloy is used for valve seats and discs, piston valves and sleeves, pump parts, and where resistance to galling and hardness at elevated temperatures are important factors.

The physical properties are given in Table I.

Table I
Physical Properties of Nickel-Copper-Silicon Casting Alloys

	As Cast 3% Si	As Cast or Rehardened 4% Si
Ultimate tensile strength, psi. (average ¹)	25,000	110,000
Yield strength, .2% offset, psi. (average)	50,000	90,000
Elongation, % in 2 in. (average)	15	2
Brinell hardness, 10 mm. ball—3000 kg. load	190	300
Rockwell C hardness	15	32
Charpy impact resistance, ft.-lb. (approx.)	40	4
Modulus of elasticity (approx.)	26,000,000	26,000,000
Specific gravity (approx.)	8.65	8.50
Weight per cu. in., lb. (approx.)	0.314	0.308
Pattern maker's shrinkage, in. per ft.	1/4	1/4
Solidification range, °F.	2,300-2,400	2,250-2,350
Electrical resistivity ohms/ml ft. 25°C. (approx.)	370	380
Coefficient of thermal expansion, per °C.	{20-100°C.} (approx.)	12.3 × 10 ⁻⁶
	{20-450°C.} (approx.)	15.1 × 10 ⁻⁶

¹Tension values determined from 1/2 in. dia. specimens, separately cast in green sand molds and the test specimens machined therefrom.

*Development and Research Division, International Nickel Co., New York.

^bTrade name "H" Monel. ^aTrade name "S" Monel.

Nickel-Molybdenum-Iron and Nickel-Molybdenum-Chromium-Iron Alloys

By Burnham E. Field*

Molybdenum metal has a high degree of resistance to chemical corrosion, particularly hydrochloric acid. It is, however, difficult to produce this metal in the form of sheet and fabricated apparatus, so it is used in the form of an alloy that will retain as much of the corrosion resistance of the molybdenum as possible.

Nickel-Molybdenum-Iron Alloys—A nickel-base alloy,¹ with approximately 30%

Table I—Physical Properties

	Alloy A	Alloy B	Alloy C
Specific gravity,			
g. per cu. cm.....	8.80	9.24	8.94
lb. per cu. in.....	0.318	0.334	0.323
lb. per cu. ft.....	549	577	558
Thermal conductivity, cal./sq. cm./cm./sec./°C.....	0.04	0.027	0.03
B.t.u./sq. ft./in./hr./°F.....	116	78.5	87
Mean. coeff. of thermal expansion, per °C.			
0-100°C.....	0.0000110	0.0000100	0.0000113
0-1000°C.....	0.0000154	0.0000146	0.0000153
32-212°F.....	0.0000061	0.0000056	0.0000063
32-1800°F.....	0.0000086	0.0000081	0.0000085
Electrical conductivity mhos per cu. cm.....	7.89	7.41	7.52

Table II—Mechanical Properties

	Alloy A		Alloy B		Alloy C
	Cast	Rolled, Annealed	Cast	Rolled, Annealed	Cast
Ultimate tensile strength, psi.....	69,000- 77,500	110,000- 120,000	75,000- 82,000	130,000- 140,000	72,000- 80,000
Yield point, psi.....	42,500- 45,000	47,000- 52,000	55,000- 57,000	60,000- 65,000	45,000- 48,000
Elongation in 2 in., %.....	8-12	40-48	6-9	40-45	10-15
Reduction of area, %.....	16-18	40-54	10-13	40-45	11-16
Hardness, Rockwell B.....	85-94	94-97	92-99	96-100	89-97
Hardness, Brinell.....	155-200	200-215	190-230	210-235	175-215
Izod impact strength, ft.-lb.....	25-35	62-77	11-16	68-78	.....
Erichsen value, depth in mm. ....	.....	10-11	.....	10-11	.....
Short time ultimate tensile strength, psi.					
at: 500°C.....	.....	90,000	.....	115,000	.....
700°C.....	.....	55,000	.....	85,000	.....
900°C.....	.....	40,000	.....	50,000	.....
1000°C.....	.....	23,000	.....	25,000	.....
For less than 1% creep per year at 900°C., max. load, psi.....	.....	1,500	.....	.....	.....
Modulus of elasticity.....	.....	27,000,000	30,750,000	28,500,000	.....

molybdenum, and 5% iron and 65% nickel, can be supplied as castings, forgings, hot rolled bars, strip, plate, sheet, rods, wire, and welded tubing. This alloy can also be machined. It is resistant to hydrochloric acid in any strength at practically all temperatures, and to sulphuric acid up to 60% concentration of boiling acid. Under these conditions the penetration of the acid is not over 0.003 in. per month, as is shown in Table III.

For many applications in which the corrosive conditions are not so severe as to require the use of the alloy described, it can be made more workable by replacing some of the molybdenum with iron. This alloy,² containing approximately 20% molybdenum, 20% iron, and 60% nickel can be forged and rolled somewhat more readily than the alloy with the higher molybdenum content, although it is more

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¹"Hastelloy" alloy B.

²"Hastelloy" alloy A.

difficult to work than steel. This alloy resists hydrochloric acid up to 160°F., sulphuric acid of any strength up to 160°F., and 25% sulphuric acid up to the boiling point. Under these conditions, laboratory tests show the alloy to have a penetration rate of not more than 0.004 in. per month. This alloy can also be readily welded and machined. It is available in the same forms as the alloy containing more molybdenum.

High Temperatures—In mechanical properties, these two alloys are comparable in strength and ductility to alloy steels as given in Table II. As they have good toughness, strength, and machining qualities, they are used in the design of chemical plant equipment and for high temperature work.

Austenitic in Nature—These two alloys are similar in structure to austenitic alloys such as the 18-8 chromium-nickel steels. They contain a small proportion of carbides, even when they have been cooled rapidly from a high temperature. Like other austenitic-type alloys, they are appreciably hardened by cold work with an increase in the yield point and ultimate strength, and a corresponding reduction in ductility. The recommended annealing procedure is to heat them to a temperature of between 2100 and 2150°F., hold them at this temperature a short time according to the thickness of the material, and follow by rapid cooling, depending upon the size and shape of the part. This treatment softens the alloys and develops their high corrosion resistance.

Table III—Results of Corrosion Tests

(Rate of penetration is expressed in inches per month and acid concentrations are expressed in percentage by weight.)

	Alloy A	Alloy B	Alloy C
Sulphuric acid, 10%, boiling.....	0.003	0.0002	0.0042
25%, boiling.....	0.004	0.00015	0.0039
60%, boiling.....	0.033	0.0028	0.061
98%, boiling.....	0.64	0.038	0.028
Hydrochloric acid, 10%, 160°F.....	0.002*	0.0033*	0.0026*
10%, boiling.....	0.028	0.0016	0.052
37%, 160°F.....	0.0017*	0.0012*	0.0068*
37%, boiling.....	0.022	0.0019	0.026
Wet chlorine gas, saturated vapor, room temperature.....	.....	.....	0.0032 max.
Nitric acid, 10%, room temperature.....	.....	.....	0.00096
10%, boiling.....	.....	.....	0.0036
70%, room temperature.....	.....	.....	0.00039*
70%, boiling.....	.....	.....	0.165*
Phosphoric acid, pure			
10%, room temperature.....	0.00018	0.00013	0.0000067
10%, boiling.....	0.0023	0.00015	0.00012
50%, boiling.....	0.0027	0.00014	0.00025
85%, boiling.....	0.068	0.00013	0.040
Phosphoric acid, technical			
10%, boiling.....	0.00082	0.00030	0.00030
50%, boiling.....	0.0027	0.0018	0.0018
85%, boiling.....	0.0039	0.0028	0.0025

*Aerated test.

Chromium Confers Oxidation Resistance—Chromium as an alloying element confers resistance to the oxidizing solution type of corrosion. In another nickel-base alloy,* approximately 15% chromium is substituted for part of the iron in the analysis of the second alloy described. This alloy, containing 15% chromium, 17% molybdenum, 8% iron, and 60% nickel, meets many corrosive conditions. It is available only in castings, as it is not particularly amenable to forging or rolling. It can be welded satisfactorily and can be machined at low speeds. This alloy resists the attack of oxidizing types of solutions, such as wet chlorine gas and ferric chloride. It is used for chlorinating equipment, cast pipe, valves, pumps, agitators and other forms of equipment for handling wet chlorine or hypochlorites.

Toughness—This nickel-molybdenum-chromium-iron alloy has a strength comparable with that of low or medium carbon cast steel, and although its ductility is not as high as that of steel, it has fair toughness, as shown in Table II, for a cast material. This alloy is not excessively hard, but its structure makes machining—and to an even greater degree, rolling, difficult. Its machinability can be improved, however, by annealing for about two hours at 2200-2250°F., and air cooling.

*"Hastelloy" alloy C.

This heat treatment to improve the machinability of the alloy also results in an increase of both ductility and corrosion resistance. Castings of this alloy are capable of being ground to an excellent finish and can be polished to a high luster. This property is important for applications such as valve seating surfaces and shafts or shaft sleeves which operate in packing glands. Sheets of this alloy cannot be rolled commercially in large sizes, but small sheets are available.

Properties—Tables I, II, and III give the physical, mechanical, and chemical properties of these alloys.

Polishing Nickel and Its Alloys for Metallographic Examination

By R. Vines*

When polishing nickel and its alloys, the avoidance of pitting or loss of inclusions is generally important and a higher grade polish is required with nickel alloys than with copper base materials where considerable metal can be removed in etching.

Samples should not be larger than about 1 x 1 in., preferably about $\frac{1}{2}$ x $\frac{1}{2}$ in. Small samples should be mounted in Bakelite, Lucite or clamps. It is also advisable to have the breadth of the sample greater than the height to minimize rocking and rounding of the edges during polishing. The selected specimen is filed or ground on abrasive wheels, using a light pressure to minimize surface distortion, to a roughly plane surface and then ground on a series of increasingly finer grit abrasive paper discs revolving at 300-600 r.p.m. Usually carborundum papers with grit sizes of 180, 240, 320 and 400 are used although some prefer an alumina grit 400 paper. The grinding on each paper should be at 90° to that of the preceding operation and should be continued until all scratches left by the coarser grit are removed.

Dry grinding on the last abrasive disk is the most critical step as the wet polishing time and the pitting tendency is governed by the depth and uniformity of scratches here produced. In order to get the shallowest scratches possible with this paper, it is advisable to use a well worn or a graphited paper for the final dry grinding.

The procedure following dry grinding depends upon the examination desired, that is, the structure or inclusions. In either case the specimen is carefully washed prior to wet polishing. The wet polishing wheels, which should be free from vibration, are preferably run at rather slow speeds of about 300-400 r.p.m.

Structure Polish—The specimen is polished on a wheel covered with a good grade of billiard cloth charged with a water suspension of No. 600 alumina abrasive. Care should be taken to have the wheel wet enough to prevent dragging but excess water increases the tendency to pit and should be avoided. The pitting tendency can also be minimized by continually turning the specimen on its vertical axis or rotating it in a direction opposite to that of the wheel. When all scratches from the preceding wheel have been removed, the specimen is washed and finish polished on a billiard cloth covered wheel moistened with a relevelated alumina settling at a rate of about 1 in. per hour.

Inclusion Polish—The specimen, which has been carefully finished on graphited 400 paper, is washed and polished on a flat crepe silk covered wheel charged with alumina.

Reference

J. R. Vilella, *Metallographic Technique for Steel*, A S M., 1938

*The International Nickel Co. Inc., Research Laboratory, Bayonne, N. J.

Etching Nickel and Its Alloys for Metallographic Examination

By W. A. Mudge*

Nickel, monel metal, and other nickel-copper alloys may be most satisfactorily etched for microscopic examination with nitric acid solutions. The two following

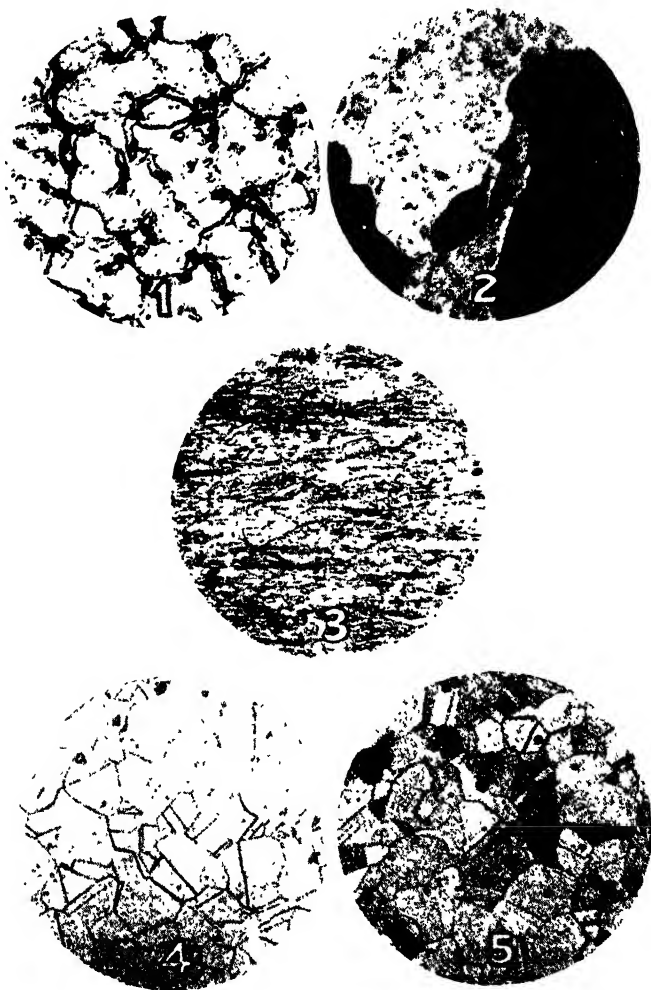


Fig. 1—Cast monel metal etched with the flat solution
Fig. 2—Same, but etched with the electrolytic solution.
Fig. 3—Cold rolled monel metal etched with the flat solution
Fig. 4—Annealed nickel etched with the flat solution.
Fig. 5—Same, but etched with the electrolytic solution

*International Nickel Co., Huntington, W. Va.

solutions which give excellent results with both cast and wrought products are as follows:

Flat Etching Solution

50 cc. of conc. nitric acid
50 cc. of glacial acetic acid

Electrolytic Contrast Etching Solution

10 cc. conc. nitric acid
5 cc. glacial acetic acid
85 cc. water

Use one 1.5 volts dry cell and platinum wires

The time of etching with the flat solution will vary from 5-20 sec., depending upon the nickel content of the alloy and the depth of etch required. The higher nickel content requires the longer time. Dilution with 25-50% of acetone is desirable when the nickel content of the alloy is less than 25%. The electrolytic contrast solution requires 20-60 sec. Over etching will invariably result in deep pitting.

In order to avoid staining, particularly with the flat etch, only clear, white nitric acid should be used. Best results are obtained at room temperatures. It is best to make a fresh solution daily. After etching, the specimen should be thoroughly washed with water and alcohol and dried quickly with a clean air blast. If a few stains are present in the flat etched specimen, they may be removed by wiping with a clean, smooth cloth or cotton. The electrolytic contrast solution will stain less than the flat solution and further cleaning will not be necessary. It is definitely superior to the concentrated hydrochloric acid solution. Good results with heavily cold worked material are obtained only with the flat solution.

Each of these two solutions serves a particular purpose. The flat solution offers the better opportunity for the detection of sonims, flaws, and porosity. The electrolytic contrast solution is more satisfactory for uniformity of grain size.

Typical photomicrographs, at 100 dia. magnification, are given to show the particular advantages of each solution.

Forging Nickel Alloys

By F. P. Huston*

The forging of nickel alloys depends largely upon proper heating, which involves not only the temperature and the time of heating, but also control of the furnace atmosphere, which is accomplished through correct combustion and the use of appropriate fuel.

With the high nickel materials, exposure of the hot metal to sulphurous atmospheres or other sources of sulphur must be avoided. Metal surfaces that have been attacked by sulphur at high temperatures have a distinctly burned appearance and, if the burning is at all severe, the material is weakened mechanically and rendered useless. The most common source of sulphur is the fuel, so care should be taken to avoid the use of fuels containing much of that element.

Fuel oil should be purchased on a specification, limiting its sulphur content to 0.5% max. The heavier oils purchased under such a specification seldom exceed 0.2% sulphur, and the lighter distillates are practically sulphur free.

Natural gas, practically free from sulphur and with high B.t.u. value, is available in many industrial centers. City gas, which usually is very low in sulphur, is used especially in small furnaces for heating small forgings.

Butane and propane are also satisfactory fuels.

The solid fuels are generally unsatisfactory because of the difficulty of providing for proper heating conditions, inflexibility in heat control, and the presence of sulphur in excessive amounts.

Heating Temperature—Nickel and high nickel alloys show important differences among themselves as to proper forging temperatures, particularly in the upper safe heating limits and in tendencies toward red shortness. Fig. 1 shows the approximate temperature ranges for hammer forging, die forging, and bending.

While heating the high nickel materials, the furnace should be maintained at a temperature about 50°F. higher than that at which the work is to be removed, and in no case should it be less than 2000°F.

Time of Heating—It is bad practice to expose nickel and high nickel alloys to combustion gases in a heating furnace for long periods after the pieces have reached a uniform forging temperature. Where a delay in forging is met, the heated pieces should be withdrawn from the furnace and reheated later when operations are to be resumed.

Approximations of the total elapsed time desirable between charging and pulling the materials are given in Fig. 2. If these ranges are observed, there will be little difficulty in forging and bending. However, these metals are stronger and stiffer than steel at forging temperature, so heavier hammer and larger machines may be required.

The Furnace Atmosphere—The furnace atmosphere should be maintained in a slightly reducing condition, with 2% or more of carbon monoxide. There is no upper limit to the permissible amount of carbon monoxide or free carbon that may be present, as nickel and high nickel alloys are not subject to carburization. The

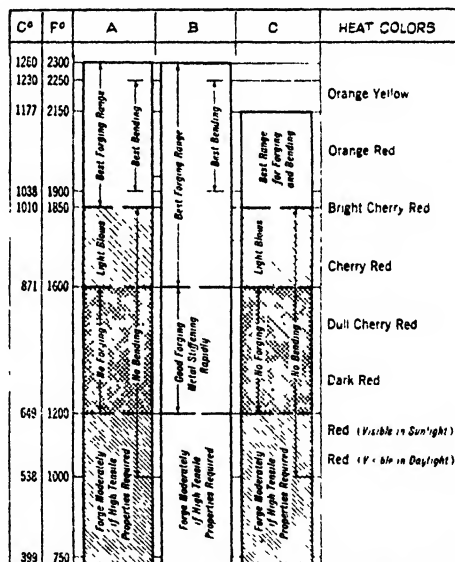


Fig. 1—Approximate temperature ranges for forging and bending operation. A = nickel 70%, chromium 15.00%, manganese 1.00%, iron 10.00%. B = nickel. C = nickel 67%, copper 30%, iron 1.00%, manganese 1.00% and carbon 0.15%.

closer the atmosphere to the neutral condition, the easier it is to maintain the required temperature.

The stack dampers should be wholly or partially closed in order to force the gases out under the furnace door, where the excess of unburned fuel will burn freely. The pressure set up in this manner prevents the entrance of air under the door or through the slot.

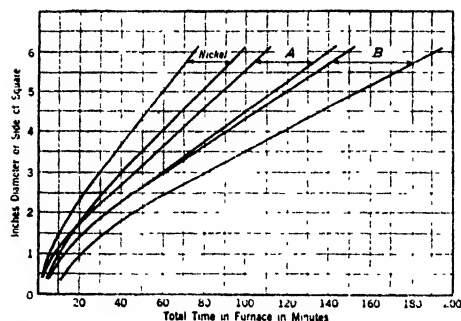


Fig. 2—Approximate time required for heating nickel and high nickel alloys. A = nickel 67%, copper 30%, iron 1.4%, manganese 1.0%, and carbon 0.15%. B = nickel 79.5%, chromium 13%, manganese 1.00%, and iron 6.5%.

cooling, through 180° flat on itself. There will be no sign of cracking if the conditions of heating have been correct. The extent of damage that may have occurred is judged by the depth of the cracks.

To determine correct forging temperature several test bars 1 x ½ x 6 in. are charged into the furnace and a single bar pulled at various temperatures. Each bar is then bent immediately through a 180° bend. The work must be done as rapidly as possible to avoid an excessive drop in temperature while the piece is being bent. When the forging temperature is correct, there will be no sign of cracking at the sharp corners.

Forging Dies—The choice between carbon and alloy steel die blocks for drop forgings and pressings depends largely on the shape and size of the piece, the quantity to be produced, and the material. Dies of 0.80% carbon steel, hardened and tempered to 60 Scleroscope, can be expected to give a good life on the smaller forgings.

Alloy steel dies are necessary for the larger or more intricate shapes and for all forgings in the high nickel-chromium alloy except small, simple shapes.

Trimmer dies should be made of high speed steel, with the cutting edge ground to a considerable rake. They should be set up closely enough to cut tissue paper. The trimming may be done either hot or cold.

It is important that combustion take place before the mixture of fuel and air comes in contact with the metal. If the combustion and heating are both done in the space above the furnace hearth, it is necessary to protect the work by shielding it with steel plates placed so as to prevent the unburned fuel from coming in contact with the hot nickel metal.

Checking Heating Conditions and Forging Temperatures—Before charging the stock in the furnace, it is advisable to check the heating conditions. A test can be made by heating a bar ½ in. dia. or ½ x 1 in. flat, to the required temperature and holding it in the furnace for 10 to 15 min. at temperature. The piece is then either water quenched or air cooled and bent, after

Machining the High Nickel Alloys

By W. F. Burchfield*

Cutting Materials—For general machining of nickel and its alloys, high speed steels of the 18-4-1 type, with 0.70-0.75% carbon content are the most satisfactory. For light cuts and high speed machining, the high speed steels containing cobalt and molybdenum are preferable.

Improved cutting materials, such as the cemented carbide, when used under proper conditions, will prove superior to the high speed steels.

Tool Angles—Tools for cutting high nickel-copper (67-30%) alloys and nickel differ from those properly ground for cutting mild steel only in that a slightly larger true rake angle back from the cutting edge, is required. This holds true for all types of cutting tools.

When machining hard, high nickel-copper alloys, the clearance angle should be kept at a minimum. On heavy, rough machining it is highly advantageous to grind a small land approximately $\frac{1}{2}$ in. wide at the cutting edge, as shown in Fig. 1 and 2.

Lubricants—Though rough turning, rough planing and shaping may be done dry, it is essential to use a cutting oil for all other cutting operations. The correct use of a good cutting oil increases the machining speed about 25% and results in a smoother finish, which is important on machined parts which are to withstand corrosive conditions.

Sulphurized oils give best results. This type of oil may slightly discolor the work but the tarnish is readily removed by soaking the work for 20-30 min. in a cold 10% solution of sodium cyanide.

All lubricants should be thoroughly removed from the machined pieces if they are to be subjected to high temperatures either during subsequent fabrication or in service.

Table I
Recommended Feeds and Speeds for Automatic Screw Machining of High Nickel-Copper Alloys (Free Machining)

Operation	Width of Cut in in.	Feed in in.	Speed in ft. per min.
Box Tool:			
Roughing	$\frac{1}{2}$	.006	100-125
	$\frac{3}{8}$	.005	100-125
	$\frac{1}{4}$	.004	100-125
Finishing . . . . .	.005	.010	100-125
Cut-off:			
Circular tool	$\frac{1}{16}$ - $\frac{1}{8}$	.001	100-125
Straight tool, stock under $\frac{1}{8}$ in dia. . . . .	.....	.0005	100-125
Forming tool.			
Circular	$\frac{1}{8}$ - $\frac{1}{4}$	.0006	100-125
	$\frac{3}{8}$ - $\frac{1}{2}$	.0005	100-125
	$\frac{5}{8}$ - $\frac{3}{4}$	.0004	100-125
	1	.00025	100-125
Balance turning tool			
Turned dia. under $\frac{3}{2}$ in	$\frac{1}{2}$	.006	100-125
	$\frac{3}{4}$	.005	100-125
over $\frac{3}{2}$ in.	$\frac{1}{4}$	.012	100-125
	$\frac{3}{8}$	.010	100-125

Turning and Boring—The practical lathe set-up for turning and boring is the same as for mild steel. The only specific instruction is that the cutting edge of the tool be set so that when cutting it is on the center of the work, Fig. 3. Best results are obtained with deep cuts and light feeds.

Roughing tools for turning are shown in Fig. 4, 5 and 6. Fig. 7 and 8 show finishing tools for turning. Lathe tools for machining high nickel-copper (67-30%) castings are shown in Fig. 9, 10 and 11.

Table I gives recommended speeds and feeds for automatic screw machine turning for free machining high nickel-copper alloys.†

*Development and Research Div., International Nickel Co., Inc., New York.

†"R" Monel.

Drilling—Standard twist drills, as furnished by drill manufacturers, have proper angles for drilling high nickel-copper alloys and nickel. See Fig. 12 for recommended drills for drilling these wrought alloys and Fig. 13 for cast high Si-Cu-Ni alloys. Only high speed steel drills should be used, and polished flutes are preferable. For maximum cutting speeds use heavy duty drills for under $\frac{1}{4}$ in. holes, and cobalt high speed drills for the larger sizes. Sulphurized cutting oils give best results. The recommended speeds for nickel and 67% nickel-30% copper alloy are between 40-60 ft. per min. with the same feeds commonly recommended for mild steel.

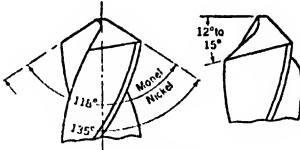


Fig. 12

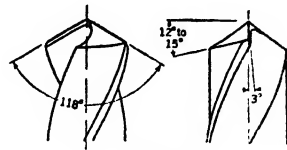


Fig. 13

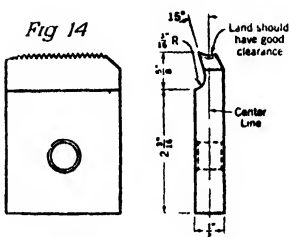


Fig. 14

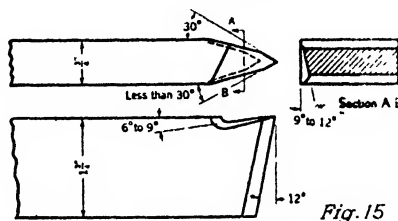


Fig. 15

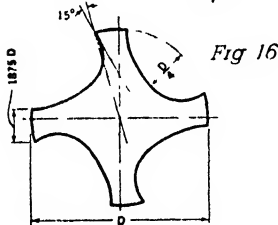


Fig. 16

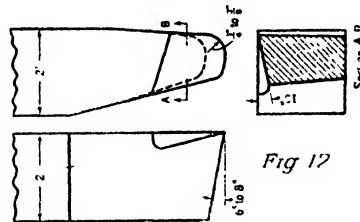


Fig. 17

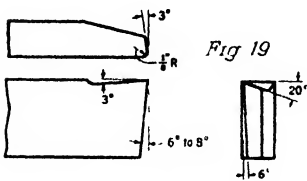


Fig. 18

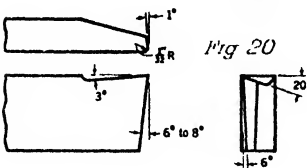


Fig. 19

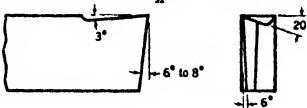


Fig. 20

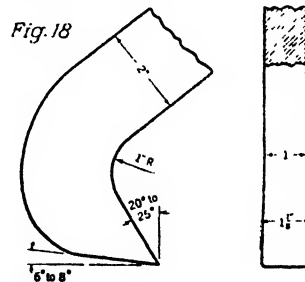


Fig. 21

Fig. 12—High speed steel drill with standard angles.

Fig. 13—High speed steel drill for special nickel alloy castings.

Fig. 14—High speed steel chaser for thread turning, showing 18° back rake.

Fig. 15—Lathe threading tool.

Fig. 16—High speed steel tap, showing desirable 18° rake back from cutting edge.

Fig. 17—Roughing planer tool.

Fig. 18—Finishing planer tool.

Fig. 19—Roughing shaper tool for depth of cut up to $\frac{1}{4}$ in.

Fig. 20—Finishing shaper tool for depth of cut up to $\frac{1}{16}$ in.

Reaming—Spiral fluted, high speed steel reamers with narrow lands and well polished flutes, are recommended. Reamers must be kept sharp at all times. Speeds for reaming are approximately 25-35 ft. per min. for nickel and the 67% nickel-30% copper alloy, and lower speeds for some of the special nickel alloys. Reaming feeds are approximately twice the recommended drill feed for the same size hole.

Thread Chasing—Thread chasing should be done with self-opening dies. The dies should have a 15° back rake, as shown in Fig. 14, instead of the usual 7-8° used on dies for steel. A speed of 20-25 ft. per min. is suggested for thread chasing nickel-copper alloy. For free machining nickel-copper alloys, speeds of 25-35 ft. may be employed.

Lathe Threading—Lathe threading is done the same as with any other metal. In cutting 67% nickel-30% copper alloys, the tool should have a back rake angle of 6-9° and a side rake angle of 9-12°, as in Fig. 15. V-threads may be machined in this alloy and nickel at speeds of 25 ft. per min. with light cuts, and Acme or straight threads at approximately 10-15 ft. per min. For other harder nickel alloys it may be necessary to reduce these speeds to 15 ft. per min. for V-threads, and 5-10 ft. per min. for straight or Acme threads.

Tapping—National standard, four-fluted high speed steel plug taps, with ground threads and 7° spiral flutes, or four-fluted, spiral pointed plug taps, are recommended for machine tapping. The plug taps have a four or five thread chamfer. If more chamfer may be tolerated, it is advantageous to extend the taper. The flutes should be ground to give approximately a 15° lip, and the tap should also be "backed off," Fig. 16. On 1¼ in. and larger sizes, the skip thread tap gives excellent results.

The 67% nickel-30% copper alloy and nickel may be tapped at a speed of 20-25 ft. per min. Free machining nickel-copper alloys may be tapped in automatic machines at 25-35 ft. per min.

Planing—The set-up for planing or shaping is no different than for mild steel. Roughing is usually done dry, but for improved surface it is advisable to use a cutting oil for finishing cuts and for parting.

Correct designs of planer tools are shown in Fig. 17 and 18, and for shaper tools in Fig. 19 and 20. Table II lists some feeds, cuts and speeds used on production jobs and will serve as a guide in setting up for planing.

Table II
Feeds and Speeds for Planing
(Heavy Work)

	—Roughing Tool— Fig. 17				—Finishing Tool— Fig. 18			Parting Tool Fig. 2a
Depth of cut, in.	1/8	1/4	3/8	1/2	.020	.015	.010	.005-.010
Feed, in.	3/32	1/8	5/32	3/16	1/16	1/32	3/64	....
Speed, ft. per min.								
Forged, nickel-copper alloy and nickel	25	25	25	25	25	35	30	30
Forged, unhardened special nickel-copper alloys	15	15	15	15	15	25	20	20

Milling—Milling chips from these materials do not break up into fine shreds or powder but tend to curl. To facilitate the removal of this type of chip, the cutter should be ground with a 10-15° back rake from the cutting edge. Coarse tooth cutters are preferred. Plain or barrel milling cutters should be of the heavy-duty, spiral fluted type. Alternating tooth or interlocking side millers are best for deep holes or for slitting. If only straight tooth milling cutters are available, the sides of the teeth should be cut on a slight taper, widest at the cutting edge. For narrow slotting, high speed steel slitting saws with alternate teeth chamfered, are most satisfactory. This type of circular saw, which is used for cutting copper, is ground concave on the side for clearance.

The surface speed and feed of milling depend a great deal on the strength and rigidity of the milling machine. For general practice, in milling 67% nickel-30% copper alloy and nickel, an average cutting speed of 50-65 ft. per min., with a feed of 0.005-0.010 in. per tooth, depending on the depth of cut, is usually satisfactory. With other harder nickel alloys that have not been heat treated, the surface speed of the cutter must be reduced to around 40 ft. per min. with a feed of from 0.003-0.006 in. per tooth.

Grinding, Polishing and Buffing the High Nickel Alloys

By W. F. Burchfield*

Grinding—Welds—To grind down welds on heavy work on which the finish is unimportant, use either a No. 14 grit or No. 24 grit rubber bond wheel. When finishing light gage work for appearance, a finer wheel, such as No. 36 grit, rubber bond, is preferred.

Rubber or artificial resin bond wheels are desirable for grinding the high nickel alloys.

Avoid overheating the welds in grinding. Excessive grinding wheel heat has been known to cause cracking of welds on thin sheets.

Precision Grinding—Rubber or resinoid bond wheels are superior to vitrified bonded wheels for fine grinding. Silicon carbide abrasive yields the best cutting action and produces the best quality of finish without scratches. The wheels should be soft enough and the grinding conditions sufficiently severe to cause the wheel to yield a slight breaking down action. Always apply an abundance of good lubricant while grinding.

Following are general recommendations for precision grinding: Wheel speed, 4,800-6,000 surface f.p.m.; work speed, 25-50 f.p.m.; table traverse speed for roughing, 80-90, and for finishing, 60-75 in. per min.; feed per pass for roughing, .001-.005, and for finishing, .0025-.001 in.

Polishing (Roll Head Wheels)—This series of operations includes "roughing," "dry fining," "greasing" and "grease coloring"—all accomplished with roll head wheels. Economy is obtained in polishing only by the correct selection of wheels, abrasives, operating speed, and above all, the correct preparation of the wheels.

Artificial abrasives should be used for grits up to No. 150 grit because of their superior cutting characteristics. Turkish emery is preferable for the finer grease wheel finishes and for polishing preparatory to buffing.

In general, there should be from 40-60 grit numbers between successive polishing operations. When preparing a surface for a buff finish, cross the scratches of the preceding coarser wheel, to be assured that the coarser marks are removed.

Buffing (Loose Disc Buff)—Buffing operations performed with loose disc buffs include the "cutting-down" from the polishing scratches preparatory to obtaining a mirror finish by color buffing. The selection of wheels is highly important for buffing. The pocket type buffs, made from high count sheeting, hold the buffing compounds well and are also stiff enough to result in good cutting action. For the highest mirror finish Canton flannel buffs charged with chromic oxide compound, are used.

Tripoli compounds are used for cutting-down operations, and unfused alumina (white) or chromic oxide (green) compounds are used for color buffing. Lime compounds, such as are used for buffing nickel plate, or rouge used for coloring brass, do not have sufficient cutting or coloring characteristics for high nickel alloys and should not be used.

Satin Finish—One method of obtaining a satin finish is to polish with a grease wheel, usually No. 150 or No. 180 grit, and then grease color using a pocket type buff charged with fine emery grease. A second method is to polish first with a grease wheel or rub down the part by hand with No. 180-220 production paper, then brush with a Tampico wheel charged with fine emery grease, or if the area is large and flat, spread a combination of emery flour and oil over the surface and brush with a Tampico wheel.

Another method is by buffing with a pocket type buff charged with a greaseless compound. This compound is a moist mixture of glue and abrasive in stick form, which is charged to a loose disc buff. It is obtainable in several grades. The compounds produce a very pleasing satin finish.

Cleaning—The final operation on all finishing jobs where polishing and buffing compounds have been used, is to sprinkle Venetian lime, "Whiting," over the article, and rub clean with a soft rag. A Canton flannel rag should be used on a mirror finish.

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The Physical Constants of Platinum and the Platinum Group Metals

By F. E. Carter* and H. E. Stauss*

Platinum

Atomic weight.....	195.23
Crystal structure.....	face-centered cubic, $a_0 = 3.9158\text{\AA}$
Density, 20°C., g. per cc.....	21.45
Melting point, °C.....	1773.5
Boiling point, °C.....	about 4500
Specific heat, 20°C., cal. per g. per °C.....	0.0324
Latent heat of fusion, cal. per g.....	26.9
Latent heat of vaporization, cal. per g.....	630
Linear coefficient of expansion, 0°C., per °C.....	8.8×10^{-6}
Young's modulus, hard.....	2.41×10^7
annealed.....	2.14×10^7
Electrical resistivity, 0°C., microhms (cm).....	9.83
Temperature coefficient of electrical resistance, 0 to 100°C., per °C.....	0.003923
0-1200°C., per °C.....	0.00318
Thermal conductivity, 18°C., cal./cm. ² /cm./sec./°C.....	0.166
Specific magnetic susceptibility, 18°C.....	1.10×10^{-6}

The physical constants of the platinum metals given in the different sections of this article have drawn freely from earlier compilations.^{1, 2, 3} Where later data have become available, they have been taken into account in selecting the best values for the constants and are discussed below. The atomic weights are from the 1938 value of International Atomic Weights published by the American Chemical Society.

Crystal Structure—The best value for a_0 is that of Owen and Yates⁴ and has been given above. The value given by the International Critical Tables is 3.913 Å.

Density—The density of platinum is given in different places in the International Critical Tables as 21.45, 21.44, 21.46 and 21.5. Owen and Yates⁴ calculated the value of 21.447 at 20°C. The figure of 21.45 consequently represents a good value for the density of platinum.

Melting Point—The melting point is based upon the values of Roeser, Caldwell, and Wensel,⁵ 1773.5°C., Hoffmann and Tingwaldt,⁶ 1773.8°C., and Schofield,⁷ 1773.3°C. A value of 1762°C. was obtained by Ribaud and Mohr.⁸

Boiling Point—This value is based upon the work of Jones, Langmuir, and MacKay.⁹ Mott¹⁰ obtained the much lower value of 4050°C. The International Critical Tables give 4901°C. and 4300°C.

Specific Heat—A value of 0.0318 at 20°C. was obtained by Jaeger, Rosenbohm, and Bottema.¹¹

Linear Coefficient of Expansion—The value of 7.908×10^{-6} is reported by Owen and Yates,⁴ while Shinoda¹² obtained 9.9×10^{-6} from 0-1000°C.

Young's Modulus—These are the values of Grüneisen.¹³ Jacquerod and Mügeli have found the much higher value of 2.82×10^7 for annealed platinum. Purity and physical state may influence this property so much that no decision between the values can be made.

General—Platinum is probably the metal that suffers most from experimenters working with only small quantities. Thus, determinations of the physical constants of platinum are not only few in number, but show a wide variation from observer to observer. Some of the latter trouble probably has been increased further by the use of commercial metal, without consideration of the purity.

Palladium

Atomic weight.....	106.7
Crystal structure.....	face-centered cubic, $a_0 = 3.8824\text{\AA}$
Density, 20°C., g. per cc.....	12.0
Melting point, °C.....	1554
Boiling point, °C.....	about 3800
Specific heat, 20°C., cal. per g. per °C.....	0.0587
Latent heat of fusion, cal. per g.....	36
Linear coefficient of expansion, 0°C., per °C.....	11.60×10^{-6}
Young's modulus, hard.....	1.70×10^7
annealed.....	1.38×10^7

(Continued)

*Physical Department, Baker & Co., Inc., 54 Austin St., Newark, N. J.

Electrical resistivity, 0°C., microhms (cm.)	10.00
Temperature coefficient of electrical resistance, 0-100°C., per °C.	0.00377
Thermal conductivity, 18°C., cal./cm. ² /cm./sec./°C.	0.166
Specific magnetic susceptibility, 18°C.	5.4×10^{-6}

Crystal Structure—The value given above is that of Owen and Yates.⁴ An earlier value by Owen and Iball¹² was given as 3.8850 Å. The best value of earlier work as given by the International Critical Tables is 3.859.

Density—The density of palladium is one of the elusive physical constants. The International Critical Tables list values of 12.0 at 20°C., 12.1 at 0°C., and 12.25. A value of 12.16 has found wide acceptance,^{7, 14} but is probably too high. The different fabricators give various values, mostly below 12.0. Swanger¹⁵ adopted the value of 12.0. Routine determinations of the specific gravity of commercial palladium have been made at Baker and Co. on 33 cast bars of several hundred ounces each. The average for the seventeen most dense bars was found to be 11.99. Owen and Yates⁴ calculated the density from their results as 12.027. Owen and Iball¹² obtained 12.011. Consequently a value of 12.0 seems to be the best value at present.

Melting Point—This constant has been determined by Fairchild, Hoover and Peters¹⁶ as 1553.6°C. ± 5 , and this combined with earlier results led them to adopt a value of 1553.1°C. ± 0.7 . Schofield^{17, 18} made two measurements, obtaining 1555°C. ± 2 , and 1554.4°C. ± 1 . The value of 1554 has been adopted as a good average.

Boiling Point—Two independent determinations have been made by Mott¹⁹ and by Richardson,²⁰ using arc methods. The figure quoted above is the average of their results. The International Critical Tables give the much lower value of 2200°C.

Specific Heat—The value given by the International Critical Tables is 26.2 joules per g. atom, or 0.0587 cal. per g. at 18°C. Jaeger and Rosenbohm²¹ obtained the dependence of the specific heat upon temperature. At 20°C. their results show a value of 0.0543 cal. per g. Later Jaeger and Veenstra²² found 0.0586 at 20°C. Holzman²³ obtained results showing that the specific heat at 20°C. is 0.0587. Poppema and Jaeger²⁴ obtained a formula connecting temperature and specific heat which leads to a value of 0.0586 at 20°C. Consequently the value of 0.0587 continues to be satisfactory.

Coefficient of Linear Expansion—This is the value of the International Critical Tables. A later value of 10.637×10^{-6} per °C. at 20°C. was obtained by Holzman, but this is low compared with most of the other determinations.

General—The affinity of palladium for the gases oxygen and hydrogen makes determinations of the physical properties of palladium itself very difficult. Oxygen tends to cause blistered metal of low density, while hydrogen alloys with the metal, forming the interstitial type of solid solution.

Rhodium

Atomic weight	102.91
Crystal structure	face-centered cubic, $a_0 = 3.7954 \text{ Å}$
Density, 20°C., g. per cc.	12.44
Melting point, °C.	1966
Boiling point, °C.	about 4300
Specific heat, 20°C., cal. per g. per °C.	0.0604
Linear coefficient of expansion, 0°C. per °C.	8.19×10^{-6}
Young's modulus, hard	4.25×10^7
Electrical resistivity, 0°C., microhms (cm.)	4.51
Temperature coefficient of electrical resistance, 0-100°C., per °C.	0.00436
Thermal conductivity 18°C., cal./cm. ² /cm./sec./°C.	0.210
Specific magnetic susceptibility, 18°C.	1.11×10^{-6}

Crystal Structure—This is the value of Owen and Yates.⁴ That of Owen and Iball¹² is in close agreement with it, 3.7954 Å. The figure given in the International Critical Tables is 3.820.

Density—The density is an average of various determinations. Swanger²⁵ obtained an average of 12.41 at 0°C. for vacuum melted rhodium. Rose²⁶ found a value of 12.47 for melted, forged metal. The International Critical Tables give 12.2 and 12.5. In his tabulation of data of rare metals, Swanger²⁵ listed the density of rhodium at 20°C. as 12.46. From X-ray data, Owen and Iball¹² calculated 12.428; and Owen and Yates,⁴ 12.414. In view of the X-ray data, a density of 12.41 would seem a fair value, but higher values have been found, and the figure of 12.44 used by Carter² has been continued.

Melting Point—This is the value of Roeser and Wensel.²² The earlier determination of Wensel, Roeser and Caldwell, as reported by Swanger,²³ led to the value $1985^{\circ}\text{C.} \pm 10^{\circ}$. The International Critical Tables give 1955°C.

Boiling Point—This is the average of the results of Mott² and Richardson,²⁴ 4000°C. and 4500°C. , respectively. The value given by the International Critical Tables is $> 2500^{\circ}\text{C.}$

Specific Heat—This is the average of the figures of Holzman and of Jaeger and Rosenbohm. The International Critical Tables give 0.059 cal. per g. per $^{\circ}\text{C.}$

Linear Coefficient of Expansion—This value is from the International Critical Tables. It is in only fair accord with the later determinations. Swanger,²⁵ obtained 8.3×10^{-6} in the temperature interval, 20 – 100°C. , while the International Critical Tables give 8.59×10^{-6} between 0°C. and 100°C. The results of Holzman seem to be low, being 7.628×10^{-6} at 20°C. A very recent determination by Ebert²⁶ gives the figure 8.5×10^{-6} between 0°C. and 100°C.

Electrical Resistivity—This is Swanger's²⁷ figure. The International Critical Tables give 5.1 in v. I., p. 103 and 4.70 at 0°C. in v. VI., p. 136. Nemlow and Woronow²⁸ give a value 6.02, which seems too high.

Temperature Coefficient of Electrical Resistance—This value is from Swanger.²⁷

Iridium

Atomic weight.....	193.1
Crystal structure.....	face-centered cubic, $a_0 = 3.8312\text{\AA}$
Density, 20°C. , g. per cc.....	22.4
Melting point, $^{\circ}\text{C.}$	2454
Boiling point $^{\circ}\text{C.}$	about 4900
Specific heat, 20°C. , cal. per g.....	0.0309
Linear coefficient of expansion, 0°C. , per $^{\circ}\text{C.}$	6.41×10^{-6}
Young's modulus, hard.....	7.47×10^7
Electrical resistivity, 0°C. , microhms (cm.).....	6.08
Temperature coefficient of electrical resistance, 0 – 100°C. , per $^{\circ}\text{C.}$	0.00392
Thermal conductivity, 18°C. , cal./cm. ² /cm./sec./ $^{\circ}\text{C.}$	0.141
Specific magnetic susceptibility, 18°C.	0.14×10^{-6}

Crystal Structure—The value of a_0 is from Owen and Yates.⁴ Owen and Iball²⁹ give 3.8314. The figure given in the International Critical Tables is 3.823 \AA .

Density—The experimental values are divergent, and the figure above is open to question. Owen and Yates⁴ calculate the density at 22.650, and Owen and Iball²⁹ obtain 22.661.

Melting Point—This is the value of Henning and Wensel,³⁰ who determined it carefully in order to use freezing iridium as a light standard. Their result is 2454°C. A value of 2440°C. was obtained by v. Wartenburg, Werth, and Reusch.³¹

Boiling Point—This is the average of the results of Mott² and Richardson.²⁴ The International Critical Tables give $> 4800^{\circ}\text{C.}$

Specific Heat—This is the value of Jaeger and Rosenbohm.³²

Ruthenium

Atomic weight.....	101.7
Crystal structure.....	hexagonal close-packed, $a = 2.6987\text{\AA}$ $c = 4.2728\text{\AA}$
Density, 20°C. , g. per cc.....	12.2
Melting point, $^{\circ}\text{C.}$	2450
Boiling point, $^{\circ}\text{C.}$	about 4500
Specific heat, 20°C. , cal. per g.....	0.057
Electrical resistivity, 0°C. , microhms (cm.).....	14
Linear coefficient of expansion, 0°C. , per $^{\circ}\text{C.}$	8.51×10^{-6}
Specific magnetic susceptibility, 18°C.	0.50×10^{-6}

Crystal Structure—The lattice constants are from Owen, Pickup, and Roberts.³³ The International Critical Tables give 2.686 \AA and 4.272 \AA .

Density—The value calculated by Owen, Pickup, and Roberts is 12.45 at 18°C.

Boiling Point—This is the average of the results of Mott² and Richardson.²⁴ The International Critical Tables give $> 2700^{\circ}\text{C.}$

Specific Heat—This value is based on the results of Holzman.

Osmium

Atomic weight.....	190.2
Crystal structure.....	hexagonal close-packed, $a = 2.7304\text{\AA}$ $c = 4.3092\text{\AA}$
Density, 20°C., g. per cc.....	22.5
Melting point, °C.....	2700
Boiling point, °C.....	about 5000
Specific heat, 20°C., cal. per g.....	0.031
Linear coefficient of expansion, 0°C., per °C.....	5.70×10^{-6}
Electrical resistivity, 0°C., microhms (cm.).....	9
Temperature coefficient of electrical resistance 0-100°C., per °C.....	0.0042
Specific magnetic susceptibility, 18°C.....	0.05×10^{-6}

Crystal Structure—The figures are from Owen, Pickup, and Roberts. The International Critical Tables give $a = 2.714$ and $c = 4.32$.

Density—Owen, Pickup, and Roberts calculated the density at 18°C. as 22.61 g. per cc. Osmium is traditionally the most dense element; but densities calculated from lattice constants, which are probably more correct for these particular elements, indicate that this distinction should belong to iridium.

Boiling Point—The value is the average of the determinations of Mott¹ and Richardson.¹⁰ The International Critical Tables give $> 5300^\circ\text{C}$.

Specific Heat—This is the value of Jaeger and Rosenbohm.

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Properties of Platinum and Platinum Group Metals and Their Alloys

By F. E. Carter* and H. E. Stauss*

Platinum—Four grades of platinum are in common use, although in the United States there is no formal recognition of the fact.¹

In addition the 5 and 10% iridio-platinum alloys are frequently called "medium hard" and "hard" platinum respectively. The grades are shown in Table I. Usually the impurities consist of the other platinum metals, for example, iridium or rhodium, although the commercial metal may contain small quantities of base metals.

Table I
Grades of Platinum

Designation	Platinum, %	Use
Physically pure	99.99	Thermocouples, resistance thermometers
Chemically pure	99.90	Catalysts
Crucible	99.5	Laboratory Ware
Commercial	99.0	General

The properties of platinum vary with the grade, and for scientific purposes only chemically pure platinum should be used, although, in the literature, for the determination of physical properties of alloys, commercial platinum of uncertain purity has frequently been used. The physical properties of chemically pure platinum are given in Table II.²

Table II
Properties of Platinum

Brinell Hardness		Ultimate Tensile Strength, psi.		Erichsen Number		Resistivity,	Temp. Coeff.
Hard	Annld.	Hard	Annld.	Hard	Annld.	ohm/mil. ft. 0°C.	of Resist., 0-100°C.
97	42	34,000	17,000	7.8	12.2	60	.0039

In the use of platinum at elevated temperatures, reduction of the melting point by inadvertent alloying must be guarded against. Platinum should never come in contact with low fusing elements at a high temperature nor with oxides of low fusing elements under reducing conditions. It should preferably be used under oxidizing conditions.

For many purposes pure platinum itself is too soft, and it is used in alloyed form. The additions are usually iridium or rhodium, but in Europe alloys with copper are common. All the other metals of the platinum group as well as a number of base metals are used for hardeners of platinum for special purposes. The hardening effect of various metals on platinum is shown in Fig. 1.

Platinum finds use in many and diverse fields and is absolutely essential in some of them. Mention may be made of its use for catalysts and noncorrosive and high temperature equipment in the chemical industry, spinnerettes for glass fibers and rayon, electrodes, thermocouples, and resistance thermometer elements, furnace windings, general laboratory ware, electrical contact points, dental foil, and, of course, jewelry.

Palladium—This is the only member of the group, other than platinum, which is easily workable and which is used to any extent commercially, in unalloyed form. The physical properties are not greatly different from those of platinum, as shown in Table III.²

Table III
Properties of Palladium

Brinell Hardness		Ultimate Tensile Strength, psi.		Erichsen Number		Resistivity,	Temp. Coeff.
Hard	Annld.	Hard	Annld.	Hard	Annld.	ohm/mil. ft. 0°C.	of Resistance, 0-100°C.
109	46	47,000	20,000	7.6	12.0	61	.0038

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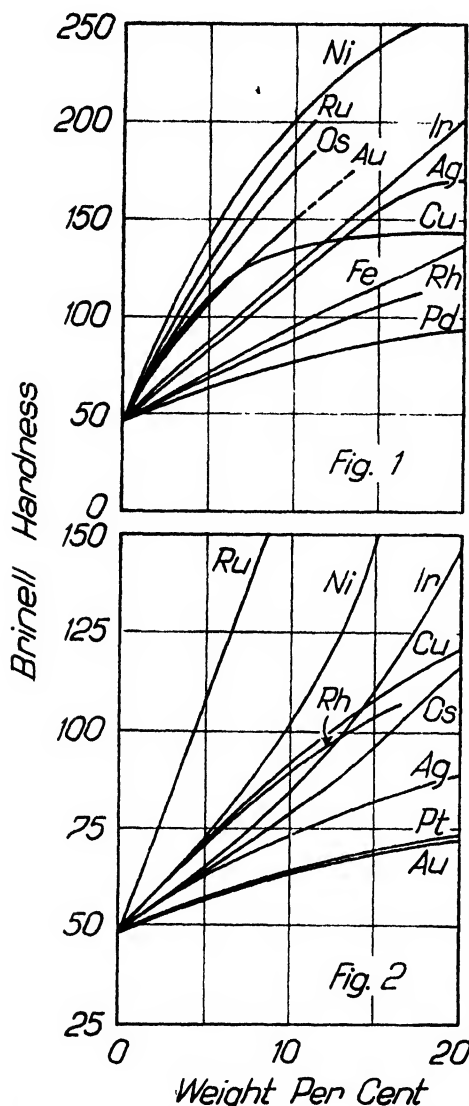


Fig. 1.—Hardness of platinum alloys. Influence of additions of other metals upon the baby Brinell hardness of platinum (2 mm. ball, 120 kg. load).

Fig. 2.—Hardness of palladium alloys. Influence of additions of other metals upon the baby Brinell hardness of palladium (2 mm. ball, 120 kg. load).

listed the properties of the alloys as compiled from published^{4,5} and unpublished work. The properties vary with the purity of the components of the alloys as well as with the manner of preparation. Therefore this table, and the following ones for alloys, should be considered as giving good average values of the properties of the alloys rather than as giving exact physical constants. In the case of hardness, not all published figures for Brinell hardness have been made with the same ratio of load to penetrator diameter, and consequently are not comparable. In the tables of

Like platinum, palladium is soft and is frequently hardened by additions of other elements. In Fig. 2 is shown the influence of several elements on the hardness of palladium.

Palladium is used in dentistry, in jewelry, and in electrical contact points; also as a catalyst, as foil for various decorative effects, and for photographic printing paper.

Rhodium—Rhodium can be fabricated only with difficulty, requiring hot working for large sizes, although small sizes can be cold rolled or drawn. The uses of the metal in its pure state are limited, being confined to the production of a nontarnishing electroplate. The physical properties have not been thoroughly studied, but what are known are shown in Table IV.⁶

Table IV
Properties of Rhodium

Brinell Hardness Hard	Resistivity, ohms/mil. ft. 0°C.	Temp. Coeff. of Resistance, 0-100°C.
390	135	.0044

Iridium, Ruthenium, and Osmium—Of these three metals, only the first has been worked so far and even iridium is extremely brittle. Iridium and osmium occur together naturally as the very hard osmiridium. Artificial alloys among these three elements, with or without platinum, are used when extremely hard noble metals are desired, such as penpoints and some electrical contact points; they are, however, too brittle to be worked.

Platinum-Iridium Alloys—The iridium alloys with platinum are the most important with respect to volume of consumption, because they are standard for jewelry. Those most commonly used are the 5 and 10% alloys, the "medium hard" and "hard" platinum of commerce, but alloys containing up to 30% iridium are in regular use for fuse wires, hypodermic needles, and electrical contacts. The important qualities of the alloys are their hardness, their high electrical resistance, and their resistance to corrosion. In Table V are

this article only baby Brinell hardnesses are given, using a two millimeter ball and a load of 120 kilograms.

Table V
Properties of Platinum-Iridium Alloys

% Ir	Brinell Hardness		Ult. Tensile Strength, psi.		Erichsen Number		Resistivity, ohms/ml. ft. 20°C.	Temp. Coeff. Resistance, 10-160°C.
	Hard	Annld.	Hard	Annld.	Hard	Annld.		
5	140	90	70,000	40,000	7.1	10.7	115	.0020
10	185	130	90,000	55,000	7.1	10.4	150	.0013
15	230	160	120,000	75,000	7.0	10.2	170	.0010
20	265	200	145,000	100,000	7.0	9.7	190	.0008
25	310	240	170,000	125,000	4.1	7.8	200	.0006
30	360	280	200,000	160,000	..	2.0	210	.0006

Platinum-Rhodium Alloys—Of recent years these alloys have been assuming importance because of their usefulness at high temperatures. While they are not as hard as the corresponding iridium alloys, they resist to a far greater extent oxidation and the development of intercrystalline weakness at elevated temperatures. In laboratory ware they show greater stability of weight than do iridium alloys and the alloy containing 3½% rhodium is widely used for such articles. The 10% alloy is the most common in technical and chemical applications. The alloy containing 20% rhodium is used to some extent for furnace windings, and other alloys have been employed for special purposes. The properties of the alloys as gathered from the available material^{1, 2, 3, 4} are given in Table VI.

Table VI
Properties of Platinum-Rhodium Alloys

% Rh	Brinell Hardness		Ultimate Tensile Strength, psi.		Erichsen Number Annealed	Resistivity, ohms/ml. ft. 20°C.	Temp. Coeff. Resistance, 25-100°C.
	Hard	Annld.	Hard	Annld.			
3.5	120	60	60,000	25,000	11.8	100	.0022
5	130	70	70,000	30,000	11.7	105	.0020
10	165	90	90,000	45,000	11.2	115	.0018
20	210	120	130,000	70,000	10.4	125	.0014
40	290	150	.....	.....	...	105	.0014

Because of the importance of the 10% alloy, Table VII is inserted to show its resistivity at elevated temperature and its tensile strength at temperature as compared with that at room temperature, as determined on 0.050 inch wire¹ and on smaller wires (unpublished data).

Table VII
Resistivity and Tensile Strength of Platinum-Rhodium (90-10) at Elevated Temperatures

Temperature, °C.	Resistivity, ohms/ml. ft. 20°C.	Ratio of U.T.S. at temperature to that at 20°C.	
		Wire dia. 0.050 in.	Wire dia. 0.010 in. & 0.003 in.
20	114	1	1
500	203	0.66	0.71
700	236	0.54	0.57
900	267	0.38	0.43
1100	296	0.23	0.29
1300	324	...	0.15
1500	356	...	0.08

Platinum-Palladium Alloys—Palladium is sometimes added to platinum, usually to reduce the cost, the density and price of palladium being the lowest of the group. The properties of the system are shown in Table VIII.^{1, 2}

Table VIII
Properties of Platinum-Palladium Alloys

% Pd	Brinell Hardness		Ultimate Tensile Strength, psi. Annealed	Erichsen Number Annealed	Resistivity, ohms/ml. ft. 20°C.	Temp. Coeff. Resistance, 0-160°C.
	Hard	Annld.				
10	145	80	45,000	11.5	120	.0014
20	175	95	50,000	11.0	150	.0012
30	180	100	52,000	11.0	170	.0010
50	175	100	50,000	11.0	165	.0010
75	150	80	43,000	11.5	130	.0014

Other Platinum Alloys with Noble Metals—Other alloy systems which have been used or studied, although they are not in common commercial use, are given below, with such physical properties as are available.^{2, 4, 5, 11, 12, 16} Ruthenium and osmium harden platinum at a very rapid rate. Gold and silver behave the same way. The last two elements, and probably the first two, have only limited solubility in platinum at room temperature. Gold and platinum form continuous solid solutions at high temperatures, but at low temperatures form conjugate solid solutions, consequently the platinum-gold alloys in the middle of the series are age-hardenable. In commercial use, it has been gold hardened by platinum, rather than platinum hardened by gold, that has been found serviceable.

Table IX
Physical Properties of Alloys of Platinum with Other Precious Metals

Alloy	Brinell Hardness		Ultimate Tensile Strength, psi.		Erichsen Number	Resistivity, ohms/mil. ft. 20°C.	Temp. Coeff. Resistance, 25-100°C.
	Hard	Annl.	Hard	Annl.			
5% Ru	210	130	115,000	60,000	...	190	.00085
10% Ru	280	190	150,000	85,000	...	260	.00083
5% Os	...	120	.....	.....	...	...	.....
10% Os	...	175	.....	.....	...	...	.....
5% Au	175	100	.....	.....	...	135	.....
10% Au	220	150	.....	.....	...	145	(0-100°C.)
60% Au	225	175	.....	77,000	6.9	155	.00037
70% Au	195	135	.....	65,000	9.7	155	.00059
80% Au	160	105	.....	58,000	11.3	120	.00054
90% Au	105	60	.....	36,000	12.2	70	.00098
5% Ag	..	80	.....	52,000	..	180	.00065
10% Ag	..	125	.....	78,000	..	290	.00055
20% Ag	...	172	.....	128,000	..	320	.00050

Platinum Alloys with Base Metals—Alloys of platinum with base metals are of interest because of the special properties that may be obtained. When the base metal addition is low, nobility at room temperature is frequently little impaired. The platinum-copper series has long been of interest because of the age hardening property of the alloys.⁹ Platinum-nickel alloys form a continuous series of solid solutions, one of which, the 5% nickel alloy, has been used as the filament in amplifying tubes. The platinum-iron alloys are of interest because of their magnetic properties, alloys containing more than 17% iron being strongly magnetic. The properties of the alloys are shown in Table X.^{2, 5, 9, 10, 11, 12}

Table X
Physical Properties of Platinum Alloys with Base Metals

Alloy	Brinell Hardness Annealed	Ultimate Tensile Strength, psi.		Resistance, ohms/mil. ft. 20°C.	Temp. Coeff. Resistance, 25-100°C.
		Hard	Annealed		
5% Ni	140	103,000	65,000	140	.0020
10% Ni	200	.....	.....	180	.0013
20% Ni	270	.....	.....	...	.0009
5% Cu	110	92,000	63,000	227	....
10% Cu	135	.....	.....	335	.00015
20% Cu	145	.....	.....	540	.00016
5% Fe	70	.....	.....	...	.0011
10% Fe	95	.....	.....	...	.0005
20% Fe	140	.....	.....	...	.0009

Palladium Alloys—Palladium is used alloyed with gold, silver, or platinum, and of late, alloys using small percentages of ruthenium and rhodium have been developed for use in jewelry. Alloys with the base metals copper or nickel also find use. The silver alloys form a continuous series of ductile alloys, as do the gold alloys; the former are used for electrical contact points, the latter for spinnerettes in the rayon industry. Both ruthenium and rhodium harden palladium rapidly, but the ternary alloys including both are preferred by the jewelry trade as having a better color. Nickel hardens palladium rapidly, apparently forming solid solutions. Copper and palladium are also solid solutions, but show intermetallic compounds and transformations in the solid state at low temperatures, and so are age-hardenable. Unquestionably the most important of all palladium alloys^{13, 14} are those used in dentistry, but these are too complex to be discussed here.

The Use and Care of Platinum Ware—It is important to remember that, although platinum is not oxidized in the air at any temperature, nor attacked by any single

acid, yet there are many substances that attack and combine with it at comparatively low temperature.

The caustic alkalis, the alkaline earths, nitrates and cyanides, and especially the hydroxides of barium and lithium attack platinum at a red heat, although the alkaline carbonates have no effect at the highest temperatures. Phosphorus and arsenic attack platinum when heated with it; therefore phosphates and arsenates should not be ignited in their filter paper in the crucible. Silicon, which may be formed by the reducing action of carbon on silica, causes brittleness. Contact with compounds of easily reducible metals like lead is dangerous at high temperatures, because low fusing platinum alloys are readily formed.

Do not put platinum in the inner cone of the Bunsen flame; the carbon in this cone reacts with the platinum to form a carbide which causes brittleness and general deterioration.

Every careful analyst of necessity uses clean utensils. The habit of cleaning and polishing platinum were immediately after using is easily formed, and repays the user with increased confidence in his work as well as with the prolonged life of the article.

The loosening effect of the Bunsen flame upon the surface of platinum exposed to its action produces the familiar gray appearance which cannot be removed except by burnishing. Rubbing the surface of platinum with moist sea sand (round grains only), applied with the finger, serves to remove most impurities and to polish the metal, without material loss in weight.

Fusing bisulphate of potash or borax in the vessel and then boiling in water and polishing as above with sand is recommended by Gmelin. When it is desired to clean the outer surface of vessels in this manner, they must be placed in dishes of sufficient size to allow the fused flux to envelop completely the article to be cleaned.

Sodium amalgam possesses the property of wetting platinum without amalgamating with it, even when other metals are purposely added to the amalgam. This substance is, therefore, useful for effecting a quick and thorough cleansing of platinum. The amalgam is gently rubbed upon the metal with a cloth and then moistened with water, which oxidizes the sodium and leaves the mercury free to alloy with foreign metals. The mercury is then wiped off and the article cleaned and polished with sand, as above described.

If the existence of a base metal alloyed with the platinum is suspected, immerse the article in question first in boiling hydrochloric acid for a few minutes; then, after thoroughly rinsing with clean water, in boiling nitric acid free from chlorine. If the article is unaffected in weight or appearance, and the acid baths fail to give reaction for base metals, the absence of such is assured.

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The Tin Industry

By R. L. Hallett*

Introduction—Tin is almost unique among the important common metals in that nearly the entire production of the world comes from countries in which practically no tin is consumed. This is of particular importance with reference to the United States, which consumes approximately half of all the tin produced in the world but does not recover any appreciable amount from domestic ores. This economic situation is not due to any lack of perspective, technical knowledge, or aggressiveness on the part of American industrialists, but is solely due to the fact that as yet no commercial tin deposits have been found in the United States. This makes the United States dependent on other countries for its tin requirements.

History—Tin was known to the ancients as early as 3000 B. C. and was used by the Phoenicians, Greeks, and Romans long before the Christian era.

The principal use for tin in ancient times was for making bronzes in which tin was added to copper for hardening purposes. The Bronze Age could not have existed without tin and the ability of various peoples to obtain and use tin for making bronze weapons and agricultural implements was a major factor in the progress and dominance of ancient nations.

Tin continues to be an important metal with many important uses and is indispensable in many industries today.

Sources of Tin—The primary source of tin is the natural mineral cassiterite which is the oxide SnO_2 . This mineral, sometimes called "tin stone," is found in many parts of the world but deposits of commercial importance are relatively rare and occur in comparatively few localities. The pure mineral contains about 78.6% tin, but even in the richest commercial deposits the tin mineral is more or less intimately mixed with large amounts of other minerals from which it must be separated.

The valuable tin deposits are of two distinctly different kinds which may be classified, according to their method of formation, as vein or lode deposits and alluvial or placer deposits. In both formations the tin mineral is cassiterite but in the vein deposits the cassiterite occurs as a primary mineral deposited in solid fissure veins, while in the placer deposits the cassiterite is found in separated particles mixed with other minerals in secondary sands and gravels.

The large and important tin mines are located in Malaya, Bolivia, Dutch East Indies, Siam, China, and Nigeria which together account for about 90% of the entire virgin tin annually produced in the world.

In addition to the virgin tin produced from natural mineral deposits a large amount of secondary tin recovered from waste and scrap metal materials comes into the market.

Mining and Metallurgy—The large operating mines of Bolivia are almost entirely vein formations, whereas the mines of Malaya, Dutch East Indies, Siam, China, and Nigeria are largely placer deposits, although formations of both types are found in all of the large production areas.

A great part of the world's tin production comes from vein ores containing from 2-4% of tin and from placer gravels yielding from 1-2 lb. of tin per cu. yd. The tin ore is removed from the vein deposits by usual deep mining methods while the placer gravels are mined by dredging, hydraulic sluicing or more primitive hand methods.

The crude ore from the vein deposits is crushed to liberate the tin mineral from the waste and the crushed ore or placer gravel is treated at the mines by various mechanical methods to remove the waste minerals and concentrate the tin mineral. The crude tin concentrate contains approximately 70% of tin and is shipped to the smelters.

For economic reasons the smelting of the tin ores is largely done in a few large modern smelting plants to which the tin concentrates are shipped from the various mining districts.

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Table I
Commercial Brands of Tin*

Company and Brand	Tin %	Antimony %	Arsenic %	Lead %	Blanc %	Copper %	Iron %	Silver %	Cadmium %	Cobalt %	Nickel and Sulphur %
Consolidated Tin Smelters, Ltd.—Booth											
Williams, Harvey & Co., Ltd.—common	99.208	0.136	0.065	0.468	0.012	0.081	0.006	0.008	0.004	0.014	....
Williams, Harvey & Co., Ltd.—standard refined	99.827	0.028	0.025	0.065	0.013	0.022	0.005	0.002	..	0.013	....
Williams, Harvey & Co., Ltd.—guaranteed 99.9%	99.915	0.013	0.008	0.037	0.007	0.009	0.004	....	..	0.007	....
Cornish—common	99.180	0.139	0.080	0.440	0.020	0.118	0.008	....	..	0.015	....
Cornish—refined	99.820	0.022	0.030	0.065	0.010	0.034	0.005	....	....	0.014	....
Pennell—common	99.158	0.190	0.078	0.386	0.019	0.129	0.006	0.012	0.005	0.017	....
Pennell—special refined	99.925	0.005	0.009	0.038	0.004	0.0102	0.004	0.001	..	0.004	....
Consolidated Tin Smelters, Ltd.—Penang											
M. S. Coy—Straits	99.914	0.003	0.026	0.037	0.006	0.004	0.006	....	....	0.002	0.003
N. V. Hollandsche Metallurgische Bedrijven											
Banks	99.963	0.016	0.003	0.009	nil	0.002	0.008	..	..	....	....
Bulliton	99.941	0.002	0.013	0.009	nil	0.006	0.009	..	..	....	....
Tulip	99.871	0.048	0.033	0.023	0.003	0.013	0.009	..	..	....	....
Lamb & Flag—99.5%	99.551	0.268	0.060	0.074	0.007	0.032	0.008	....	....	....	....
Lamb & Flag—99%	99.145	0.371	0.086	0.307	0.010	0.071	0.010	..	..	....	....
Lamb & Flag—98%	98.143	0.404	0.071	1.159	0.032	0.176	0.016	..	..	....	....
Straits Trading Co., Ltd.											
S. T. Co.	99.844	0.013	0.046	0.043	0.012	0.030	0.007	..	..	0.003	0.002
Societe Generale Metallurgique de Hoboken											
U. M. H. K.	99.936	0.002	trace	0.060	trace	0.007	0.005	trace	....	nil	....

*This table represents average composition of the various brands. Compiled by the author with the assistance of D. J. Macnaughton of the International Tin Research & Development Council from information obtained from producers.

The principal tin smelting and refining plants are as follows:

Consolidated Tin Smelters, Ltd.....	Bootle, England
Consolidated Tin Smelters, Ltd.....	Penang, Straits Settlements
Straits Trading Co., Ltd.....	Singapore, Straits Settlements
Straits Trading Co., Ltd.....	Penang, Straits Settlements
N. V. Hollandsche Metallurgische Bedrijven.....	Arnhem, Holland
Netherlands East Indian Government.....	Banka, Netherlands East Indies
Societe Generale Metallurgique de Hoboken.....	Hoboken, Belgium
Yunan Tin Corporation.....	Kochiu, Yunan, China

Brands and Markets—The different tin smelting and refining companies produce and market tin under various proprietary brand names. A number of the important brands with their composition are given in Table I.

The crude tin from the Yunan Tin Corp. and many smaller Chinese smelters is refined in several refining plants in Hong Kong. The Chinese refined tin is known as Chinese No. 1 and is sold with the guarantee that it contains not less than 99% tin.

The price per pound of Straits tin at New York has varied from a low of 18.35 cents to a high of 71 cents during the ten year period from 1927 to 1937.

Consumption and Uses—The tin consumption of the world has varied from a low of 107,400 long tons to a high of 182,249 long tons during the ten year period from 1927 to 1937, and the consumption of the United States has varied between 40,600 long tons and 87,000 long tons during the same years.

The Minerals Year Book of the United States Bureau of Mines publishes some statistics showing the classification of the various uses of virgin tin consumed in the United States. For the years 1927, 1928 and 1930 the classification was as follows:

Virgin Tin Consumed in the United States

Uses	Average for 1927, 1928 and 1930, % of Total
Tin Plate and Terneplate.....	38.25
Solder	18.68
Bearing Metal	10.14
Bronze	6.00
Foil	5.88
Collapsible Tubes ..	4.55
Chemicals	4.85
Tin Oxide	1.51
Tinning (Other than Tin Plate).....	3.91
White Metal	1.35
Type Metal	0.52
Castings	0.86
Other Alloys	0.71
Miscellaneous	2.79
	100.00

While the consumption of virgin tin in the different industries varies somewhat from year to year, the above three year average figures are fairly representative and indicate the relative importance of tin for various industrial purposes.

Constitution of Tin-Antimony Alloys

By W. A. Cowan* and G. O. Hiers†

The tin-antimony alloys are of commercial importance in type metals, Britannia metal, and Babbitt for lining bearings. Another element is generally added and the tin in such a material is capable of infinite variation, while the antimony seems to be confined to a maximum content of about 25% because of the increased brittleness which it confers.

The tin-antimony system was constitutionally examined 20 years ago and the liquidus and solidus curves fixed with fair accuracy. The transformations in the solid state have not received much experimental attention and the solid solubility lines plotted in Fig. 1 are mostly hypothetical as conceived by Guertler.

The liquidus curve, represented by joining the points EDCBA, irregularly descends from 630°C., the melting point of pure antimony, to 232°C., the melting point of pure tin. Four solid solutions form the constituents that freeze out first in their respective ranges; namely; the delta solid solution, between the compositions of 100 and 50% antimony; the gamma, between 50 and 21% antimony; the beta, between 21 and 9% antimony; and the alpha, between 9 and 0% antimony.

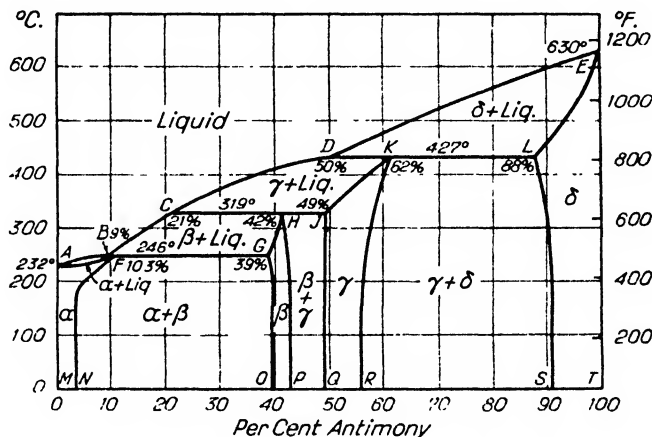


Fig. 1—Tin-Antimony Constitution Diagram

The line F N has been determined by Hanson and Pell-Walpole. The solubility of antimony drops from 10.3% at the peritectic point 246°C. to 4% at 190°C. and then gradually to 3.5% at 0°C.

The solidus curve made by joining the points ELKJHGFA is somewhat complex, due to 3 peritectic reactions at K, H, and F, which are responsible for the temperature horizontals of the solidus at 427, 319, and 246°C. The completely solid alloys consist of either a single solid solution or a mixture of 2 solid solutions, and the solid solubility curves in each case show that the solubilities decrease as the temperature falls.

An explanation of 1 peritectic reaction will serve for all three observed in this system. For instance, alloys between the compositions of 88 and 62% antimony form a mixture of solid solutions gamma plus delta on freezing at 427°C. At the invariant point K there are 3 phases in equilibrium with each other. The liquid metal, however, has an excess of tin over that indicated by K and so the liquidus continues to slope from D to C. The delta solid solution, previously in equilibrium with the liquid metal, changes to the gamma solid solution which is also in equilibrium with liquid metal in the composition range of 62-50% antimony and at 427°C.

At 49% antimony the compound SbSn probably exists and may be considered responsible for the characteristic cubic structure observed in the beta solid solution. The e.m.f. composition measurements made by Puschin show an abrupt change at this point on the curve. He has also suggested the possibility of a second compound, Sb₂Sn, but such a view is not generally maintained.

According to van Klooster and Debacher single crystals of SbSn have a simple

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cubic lattice of the NaCl type, with 4 antimony and 4 tin atoms at the corners of the unit cell. The atomic distance was found to be 3.06' A.

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Constitution of Tin-Bismuth Alloys

By W. A. Cowan* and G. O. Hiers†

Binary alloys of tin and bismuth are seldom, if ever, used industrially. These metals are, however, of considerable importance in fusible alloys, which contain in addition either or both lead and cadmium.

The system is essentially of the simple eutectiferous type with the 2 branches of the liquidus AB and CB meeting at the eutectic point, 57% bismuth, and at 135°C. (See Fig. 1.)

From 0-57% bismuth the primary constituent is the alpha solid solution of bismuth in tin and from 57-100% bismuth the primary constituent is the beta solution of tin in bismuth.

The solidus passes through the points ADBEC. Immediately after solidification alloys between 0-6% bismuth consist of the single solid solution alpha, those between

6 and 97% bismuth of a mixture of alpha plus beta solid solutions, and finally those between 97 and 100% bismuth of the single phase beta. The exact shape of the solidus curve AD and CE has not been experimentally defined.

Below the eutectic temperature the tin is less able to keep bismuth in solution and a eutectoid inversion takes place at 95°C. The approximate limits of solid solubility are given by the dotted lines FH and DH. In alloys covering

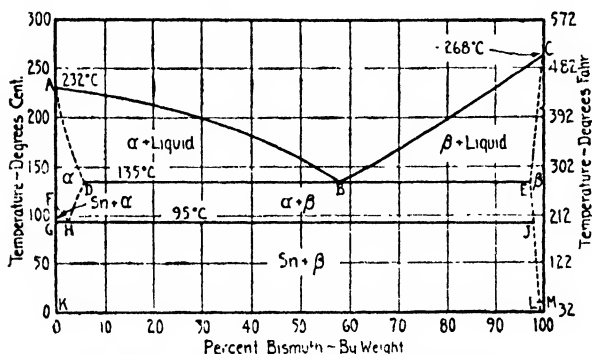


Fig. 1—Tin-Bismuth Constitution Diagram

a wide range, this transformation can be detected by sensitive cooling curve methods, as shown by the transformation horizontal GHJ. Below 95°C alloys from 0-98% bismuth are duplex in structure and contain pure tin and beta solid solution.

The solubility limit of the beta solution is approximately indicated by the line EJL, although this feature of the diagram has not received much experimental attention.

No phase change is shown in the diagram at 18°C. because bismuth has been shown to be very effective as an inhibitor in the change of beta to alpha tin. (Tin disease-gray tin.) According to G. Tammann and K. L. Dreyer, tin disease is completely suppressed by 0.5% bismuth. In a later investigation, Mason & Forgeng find 0.0035% bismuth is a preventative, provided the bismuth is in homogeneous solid solution. They state that 0.001% bismuth in uniform solution does not inhibit the transformation.

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Constitution of Tin-Cadmium Alloys

By W. A. Cowan* and G. O. Hiers†

These metals form a eutectic at 33% cadmium and at 176°C. There are three primary constituents which solidify first in the following ranges: From 0.0-3.8% cadmium, alpha; from 3.8-33% cadmium, beta; and from 33-100% cadmium, gamma.

The liquidus is designated by the line A B C D, while the solidus is obtained by joining the points A E F G H D.

Cadmium in the amount of 1.2% is soluble in tin over a considerable range in temperature, as shown in the area indicated by A E J K, representing the alpha solid solution.

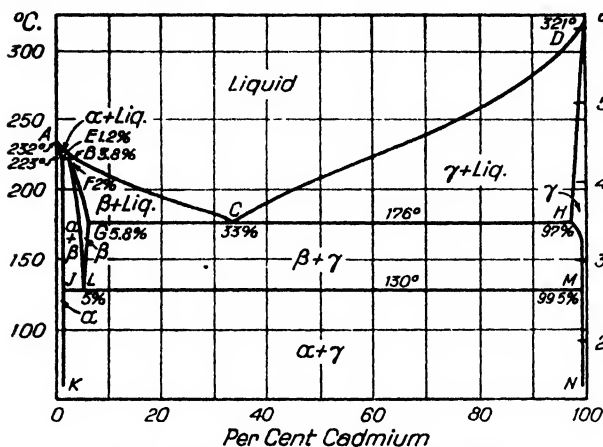


Fig. 1—Tin-Cadmium Constitution Diagram.

L G F denotes the uniphase solid solution beta. The field L M H C G represents the existence of the two solid solutions beta and gamma, while the area indicated by D H M N denotes the solid solution gamma.

The field indicated by K J L M N represents a mixture of the two solid solutions, alpha plus gamma. There is a eutectoid point at 5% cadmium and at 130°C. The eutectoid horizontal J L M exists between 1.3-99.5% cadmium. The transformation of the beta solid solution to the alpha solid solution occurs at this horizontal. Here structural transformation may be associated with the allotropic gamma to beta phase change in pure tin.

At this time, there are no positive data pertaining to the influence of cadmium in respect to the phase change which occurs in pure tin with the allotropic change from the beta to the alpha state.

The data used in plotting this diagram have been principally taken from the investigations of D. Hanson and W. T. Pell-Walpole.

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The Constitution of Tin-Copper Alloys

By W. A. Cowan* and G. O. Hiers†

The tin-copper alloys are of such great practical importance in the nonferrous industry and are of such a complex nature that it occasions no surprise to find an extensive record of careful investigation in this field. Heycock and Neville's early work on these alloys has been accepted as one of the classical researches in metallography and it is remarkable how closely their results agree with work performed with modern refinement of apparatus.

The alloys described herewith, containing from 0-50% copper, have been studied thoroughly by J. L. Haughton, who not only reviewed all previous investigations, but in his own work made use of long period annealings which are necessary in order to insure true equilibrium conditions. His diagram has been adopted by the International Critical Tables and is made the basis of this article.

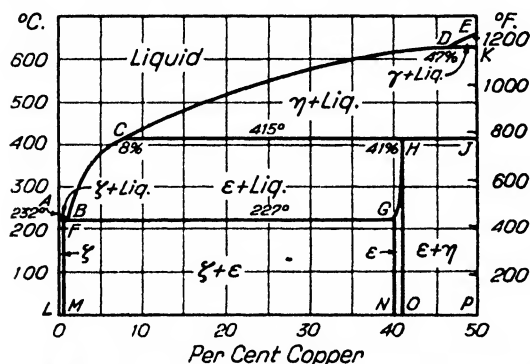


Fig. 1—Tin-rich portion of the tin-copper constitution diagram.

a uniphase solid solution, epsilon. The field M N G F consists of the epsilon solid solution and tin containing 0.2% copper in solution called zeta. The area L M F A represents the solid solution zeta.

The Liquidus Curve—The liquidus drops from the melting point of tin 232°C., to the eutectic point at 0.94% copper and at 227°C., and then rises rapidly upon further increase of copper content.

From 50-47% copper the primary constituent is the gamma solid solution. At D, 625°C., this phase reacts with liquid to form the solid solution eta. From D-C (alloys of 47-8% copper) the primary constituent is eta. At C this phase reacts with the liquid to form the epsilon solid solution which is the primary constituent separating from the liquid along the curve from C-B (8-0.94% copper). The solidus curve is formed by joining the points A F B G H J; the complicated form is due to peritectic reactions of the solid phases with this liquid.

The existence of the solid solution of 0.2% copper in tin, zeta, was found by the painstaking investigations of Haughton. According to Hanson, Sanford, and Stevens, there is no zeta solid solution.

There has been considerable dispute about the percentage of copper in the eutectic, although its location at 227°C. appears well established.

Description of Fields Shown on Diagram—The area D K E represents a mixture of the solid phase gamma, and liquid.

The field C H J K D represents a mixture of crystals of solid solution eta and liquid.

The area B G H C represents the solid phase epsilon and liquid.

The region F B A represents the solid solution zeta and liquid.

The area O P J H represents a heterogeneous mixture of the solid solutions eta and epsilon.

The area N O H G represents the solid solution zeta and liquid.

Eutectic Composition, % Copper

Investigators

Date of Report

0.9	Heycock and Neville	1903
1.0	Gurevich and Hromatko	1921
1.5	Bauer and Vollenbruck	1922-1923
1.0	Ishihara	1928
0.94	Hiers and deForest	1930
0.7-0.75	Hanson, Sanford and Stevens	1934

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Transformations in the Solid State—In the diagrams of several investigators a hypothetical transformation of the epsilon constituent to epsilon prime, has been given at 186 and 189°C. This was based largely on determinations of thermal resistance but microscopic examinations show no difference between the two solid solution structures. These horizontals are not included in Fig. 1 because of insufficient evidence and also due to the X-ray investigations of Westgren and Phragmen, who find no evidence of such transformation. Horizontals at 160 and 18°C. are also removed from the present diagram because of insufficient evidence to support inclusion. According to some investigators they are alleged to be associated with the transformations of tin in the allotropic changes: Gamma to beta and beta to alpha respectively. It is felt that a small amount of copper in tin is effective in inhibiting such transformations.

From 40-41% copper the solidus rises rapidly from 227-415°C. In this narrow field the solidified metal consists of the homogeneous phase epsilon. Long annealing at suitably high temperatures are essential to attain the equilibrium single phase structure of this epsilon solid solution.

From 41-50% copper the solidus J H at 415°C. is also part of the peritectic horizontal; H is the peritectic point.

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Constitution of Tin-Phosphorus Alloys

By W. A. Cowan* and G. O. Hiers†

The tin-phosphorus system has only been partially investigated. The alloys containing from 0-50% phosphorus were examined by thermal and microscopic methods by A. C. Vivian, who drafted a provisional diagram. The work was attended by great experimental difficulty, as it was found that for the formation of alloys above 2.5% phosphorus the vapor phase was necessary. For alloys containing more than 8.5% phosphorus, pressure above atmospheric was required. Since the pressure is usually considered invariant in metallurgical thermal concentration diagrams, the tin-phosphorus system is noteworthy and represents pioneer effort.

It has been suggested that the diagram as shown may be regarded as a sloping section cut through a three dimensional model having three variables: Concentration, temperature, and pressure. However, as the pressures used were not measured and necessarily varied in the different experiments, no definite section or plane can be considered. The investigator felt it advisable to reject the view of a three-dimensional model since the pressure functioned solely in determining the phosphorus concentration.

With this explanation and also the mode of experimentation, the diagram to be described must not in any way be regarded as final. Haughton's nomenclature has been adopted in discussing this work, as his diagram attempts a provisional representation of equilibrium conditions which is in keeping with phase rule requirements.

Alloys from the tin end of the diagram begin to solidify along the liquidus AB which mounts almost vertically up to 400°C. and then slopes to 550°C. for a phosphorus content of 8.5%, shown at the point B. From theoretical considerations Haughton shows the eutectic containing a minute quantity of phosphorus, but

as this quantity is unknown and so small, it is difficult to show on a diagram of the size plotted. Further work may establish the existence of the eutectic, but the cooling curves of Vivian certainly did not show it and for practical purposes its consideration can be rejected.

Alloys between B and C, from 8.5 to about 15.5% phosphorus, form two immiscible liquids at about 550°C. Dotted lines BB' and CC' illustrate in a limited way the concentrations and temperatures at which the conjugate solutions may exist. Somewhere just above 600°C. it is probable that the lines BB' and CC' join and the

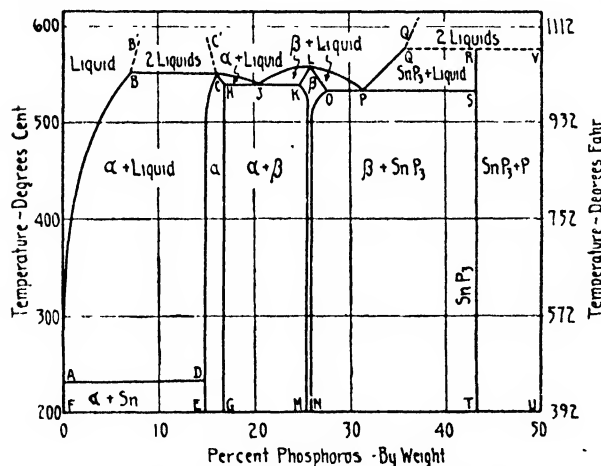


Fig. 1—Tin-Phosphorus Constitution Diagram.

liquids of these compositions are mutually soluble, one liquid phase only being present. The line BC is the liquidus for alloys of the above concentrations. Therefore the area bounded by the liquidus curve ABC and the solidus AD, which is the horizontal at 232°C. and the almost vertical solidus DC, contains the alpha solid solution plus liquid. Below the solidus AD the alloy consists of pure tin and alpha solid solution.

The area EDCHG denotes the limits of the alpha solid solution, E indicates 14.7 and G 16.3% phosphorus. The nomenclature adopted in this area is Haughton's inter-

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This article not revised for this edition.

pretation of the experimental results obtained by Vivian and the line HG shows the maximum solubility of tin in the compound Sn_3P_4 . Vivian's notation in this area is confusing and does not fulfill phase rule conditions.

The area CHJ represents two phases, alpha solid solution and liquid metal. The liquidus line CJ meets the solidus CHJ at the first definite eutectic point J at 20% phosphorus. Alloys of increasing phosphorus content begin to freeze along an ascending liquidus JL to the maximum temperature at L, the point of total freezing for a single concentration of the beta solid solution. The point L may justifiably be regarded as the compound Sn_3P_4 from its mode of freezing, but more experimental data will prove or disprove such a hypothesis. The solidus of alloys of concentrations between C and L is shown by the line CH, eutectic horizontal HJK, and line KL. The area JKL represents the existence of two phases: Beta solid solution, which is a probable solid solution of tin in Sn_3P_4 , and liquid metal.

The beta solid solution is bounded on the one side by the solidus KL and the line of solid solubility KM, and on the other side by the solidus LO and line of solid solubility ON. Vivian's results show a possible junction of solid solubility lines KM and ON at about 440°C ., but for theoretical requirements it is necessary to show a solid solution as an area and not as a line of invariant concentration.

Alloys in the area GHJKM consist of the alpha solid solution plus beta solid solution.

The area LOP denotes mixtures of beta solid solution plus liquid. The liquidus LP intersects the solidus LOP at the second eutectic P.

Proceeding to higher compositions of phosphorus the liquidus rises to the point Q at 580°C . and then supposedly proceeds along the horizontal QRV.

Alloys of composition Q and of increasing phosphorus content are believed to form conjugate solutions above 580°C . The line of liquid miscibility QQ' is drawn dotted to indicate this probability.

At about 43% phosphorus and at 580°C ., a compound which would have a formula SnP , appears and the line RST denotes its concentration. Alloys in the area ONTSP consist of two phases: The beta solid solution plus the compound SnP .

Concentrations of phosphorus greater than 43% indicate the existence in the solid state of the compound SnP , and elemental red phosphorus, but such mixtures have received little study.

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Constitution of the Tin-Antimony-Copper Alloys Used As Bearing Metals

By O. W. Ellis*

The tin-antimony-copper system has been the subject of considerable investigation^{1,2,3} but no work on the constitution of these alloys has yet been published. The following discussion, which is mainly concerned with the industrial alloys of this system, would therefore require some alteration to bring it into strict line with equilibrium requirements.

The constituents present in these high tin ternary alloys, *as cast*, are four in number, as follows:

1. The alpha solid solution, containing tin and copper. In these alloys, *as cast*, this constituent is characterized by a cored structure, which, however, can be removed by annealing the alloys for sufficient time at, for example, 100°C.

2. A constituent present in these alloys in the form of needle-shaped crystallites which vary in size according to the rate at which the alloy is cooled. It seems likely that in these alloys, *as cast*, the needle-shaped constituent, if not the intermetallic compound, CuSn, approaches it closely in composition. If these alloys are sufficiently annealed, equilibrium is reached as a result of the formation of the epsilon solid solution (see "Constitution of Tin-Copper Alloys," in this Handbook).

3. A constituent present in these alloys in the form of needle-shaped crystallites of a solid solution, eta, containing approximately 61.5% copper. These crystallites are not present in alloys containing less than 8% copper, and will not be referred to in the subsequent discussion of this system.

4. The intermetallic compound of tin and antimony, SnSb, containing approximately 50.4% antimony, which appears in the microstructure of these alloys, *as cast*, in the form of very sharply defined cubes and sections of cubes. Whether, under conditions of equilibrium, this compound would be replaced by the beta solid solution of the tin-antimony system is uncertain. The constitution of the latter system deserves much fuller investigation.

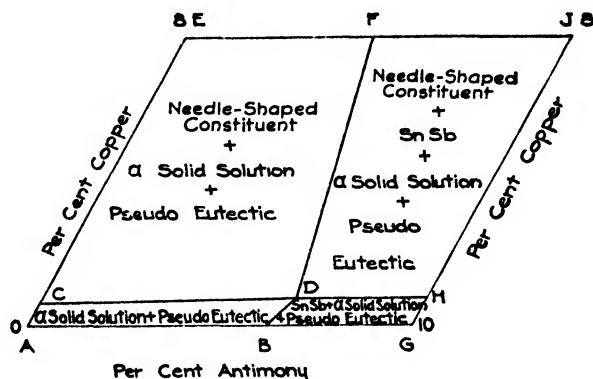


Fig. 1—Tin-Antimony-Copper Constitution Diagram.

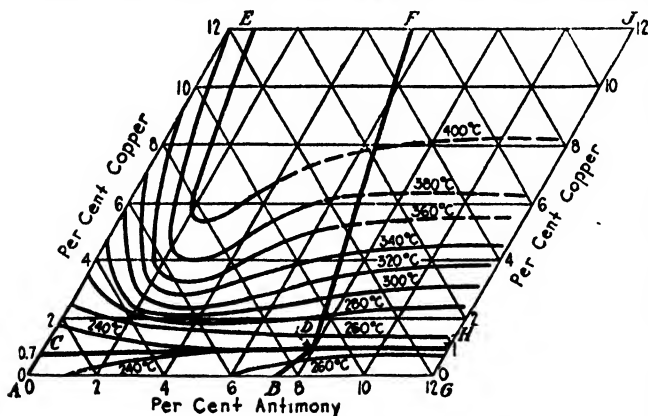


Fig. 2—Contours of liquidus surface of space model for tin corner of system.

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It is convenient to arrange the alloys in four groups in accordance with their microstructure, as shown in Fig. 1.

1. The first group of alloys, *as cast*, are characterized by a hypoeutectic structure, comprising alpha solid solution and a eutectic, or pseudo-eutectic.

2. The alloys in the second group, *as cast*, contain three micro-constituents: The needle-shaped constituent; the alpha solid solution; and the pseudo-eutectic already described.

3. The third group of alloys, *as cast*, comprise three micro-constituents: The intermetallic compound, SnSb; the alpha solid solution; and pseudo-eutectic. The proportion of pseudo-eutectic in these alloys is very small.

4. The fourth group of alloys, *as cast*, comprise four micro-constituents: The needle-shaped constituent; the intermetallic compound, SnSb; alpha solid solution; and pseudo-eutectic, of which the proportion is very small.

These four groups lie within the areas outlined in Fig. 1. Group 1 occupies the area ABDC; group 2, the area CDFE; group 3, the area BGHD; and group 4, the area DEJF.

The contours of the liquidus surface of the tin corner of the space model for this system* are shown in Fig. 2. The solidus for all the alloys covered by this diagram is 225°C. which is the eutectic temperature of the tin-copper system. In alloys which contain SnSb as a separate microconstituent, SnSb begins to crystallize on slow cooling at a temperature of 248°C. Rapid cooling has the effect of suppressing the crystallization of SnSb at 248°C. in antimony-rich alloys in the neighborhood of the boundaries BD and DF. It is possible that this effect might be of some importance in its bearing upon the antifrictional behaviour of the alloys lying near the boundaries BD and DF, and it may be well to emphasize the fact that the further removed an alloy is from these boundaries, the less likely is the normal crystallization of SnSb to be prevented.

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Structure of Tin-Antimony-Copper Alloys Used As Bearing Metals

By O. W. Ellis*

By referring to the data sheet dealing with the constitution of the tin-antimony-copper alloys it will be seen that the alloys of this system, which are of industrial importance, may be divided into 4 groups as follows:

1. The first group of alloys, *as cast*, are characterized by a structure, comprising alpha solid solution and a eutectic, or pseudo-eutectic.

2. The alloys in the second group, *as cast*, contain 3 microconstituents: The needle shaped constituent, the alpha solid solution, and the pseudo-eutectic.

3. The third group of alloys, *as cast*, comprise 3 microconstituents: The inter-metallic compound, SnSb; the alpha solid solution; and pseudo-eutectic. The proportion of pseudo-eutectic in these alloys is very small.

4. The fourth group of alloys, *as cast*, comprise 4 microconstituents. The needle shaped constituent, intermetallic compound, SnSb; alpha solid solution; and pseudo-eutectic, of which the proportion is very small.

These 4 groups lie within the area outlined in Fig. 1. Group 1 occupies the area ABDC; group 2, the area CDFE; group 3, the area BGHD; and group 4 the area DHJF.

The microstructure of typical members of each of these groups is shown in Figs. 2 to 7. In all cases the alloys were poured at a temperature of 400°C. into a vertical mold approximately 1¼ in. in dia. and 7½ in. deep. which was heated to a temperature of 100°C. prior to casting. The samples for micro-examination were cut from the castings at a point about ½ in. from the bottom. The section photographed was near the center of the casting.

Fig. 2 is the structure of an alloy containing approximately 95.5% tin, 4% antimony, and 0.5% copper. It may be taken as representative of the structure of the alloys of group 1, which lie within the area ABDC of Fig. 1. The lighter areas are sections of primary alpha solid solution of the ternary system; the darker areas are sections of pseudo-eutectic. The small white crystallites noticeable within the darker areas are of the needle shaped constituent, which is itself a constituent of the pseudo-eutectic.

Fig. 3 is the structure of an alloy containing approximately 94% tin, 2% antimony, and 4% copper. This may be considered as a representative structure of the alloys of group 2, which lie within the area CDFE of Fig. 1 (see also Fig. 4). In this photomicrograph the needle shaped constituent is clearly visible. It was the first constituent of this alloy to freeze on cooling. The gray areas are sections of the alpha solid solution of the ternary system; the black areas, containing here and there minute crystallites of the needle shaped constituent, are sections of pseudo-eutectic.

Fig. 4 is the structure of an alloy containing approximately 86% tin, 6% antimony, and 8% copper. The structure of this alloy is similar to that shown in Fig. 3. The proportion of pseudo-eutectic in this alloy is, however, so small as to make it difficult to see it at the magnification used in this photomicrograph. The proportion of pseudo-eutectic in these alloys decreases as their antimony and copper contents increase.

Fig. 5 is the structure of an alloy containing approximately 91.5% tin, 8% anti-

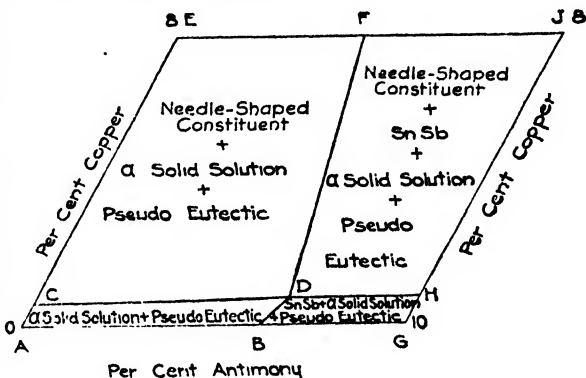


Fig. 1.—Tin-Antimony-Copper Constitution Diagram.

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mony, and 0.5% copper. This may be considered as a representative structure of the alloys of group 3, which lie within the area BGHD of Fig. 1. The outstanding



Fig. 2—Structure of an alloy containing approximately 95.5% tin, 4% antimony, and 0.5% copper. $\times 150$.
 Fig. 3—Structure of an alloy containing approximately 94% tin, 2% antimony, and 4% copper. $\times 150$.
 Fig. 4—Structure of an alloy containing approximately 86% tin, 6% antimony, and 8% copper. $\times 150$.
 Fig. 5—Structure of an alloy containing approximately 91.5% tin, 8% antimony, and 0.5% copper. $\times 150$.
 Fig. 6—Structure of an alloy containing approximately 89.5% tin, 10% antimony, and 0.5% copper. $\times 150$.

feature of this structure is the constituent SnSb, which is present in the alloy in the form of cubes, sections of which are clearly seen in the photomicrograph. This constituent was the first to separate from the melt on cooling. It is imbedded in a matrix consisting almost entirely of alpha solid solution. The proportion of pseudo-eutectic present in the alloy is so small that it is impossible to detect at the magnification used.

Fig. 6 is the structure of an alloy containing approximately 89.5% tin, 10% antimony, and 0.5% copper. This photomicrograph is a companion to Fig. 5 and is introduced for the purpose of emphasizing the apparent effect of the needle shaped constituent on the size of the cubes of the tin-antimony compound, SnSb.

Fig. 7 is the structure of an alloy containing approximately 82% tin, 10% antimony, and 8% copper. This may be considered as a representative structure of the alloys of group 4, which lie within the area DHJF of Fig. 1. Here sections of the needle shaped constituent, which was the first to freeze on cooling, and of cubes of the intermetallic compound, SnSb, which was the second constituent to freeze on cooling, are

found in a matrix of alpha solid solution. Some pseudo-eutectic is present in the structure but in such small amounts that it is difficult to detect at a magnification of 150 diameters.

It will be noted that the size of the cubes in Fig. 7 is considerably greater than that of the cubes in Fig. 6. This greater cube size is characteristic of the alloys of high copper content, other things apparently being equal. Ellis and Karelitz¹

¹O. W. Ellis and G. B. Karelitz, Study of Tin-Base Bearing Metals, Trans., Am. Soc. Mech. Engrs., 1928, MSP-50-11, p. 13.

are of the opinion that "the difference in crystal size may be accounted for by assuming that the presence of primary CuSn^3 facilitates the precipitation of SnSb and, as a result, a few large cubes are formed where, in the absence of the inoculating medium CuSn , a greater number of small cubes would be precipitated. The presence of needles of CuSn within the cubes of SnSb is a common occurrence in the alloys of high copper content."

Rapid cooling has the effect of suppressing the crystallization of SnSb in antimony-rich alloys in the neighborhood of the boundaries BD and DF of Fig. 1. It is therefore possible to obtain structures free from cubes of SnSb in certain alloys, if the same be cooled from the liquid state at a sufficient rate. This effect, in an alloy containing approximately 90% tin, 8% antimony, and 2% copper, is brought out in Fig. 8 and 9, the former representing the average structure toward the center of an ingot of this alloy, the latter the average structure near the edge. It is possible that this effect might be of some importance in its bearing upon the antifrictional behavior of the alloys lying near the boundaries BD and DF, and it may be well to emphasize the fact that the further removed an alloy is from these boundaries, the less likely is the normal crystallization of SnSb to be prevented.

In the case of alloys further removed from these boundaries the rate of cooling

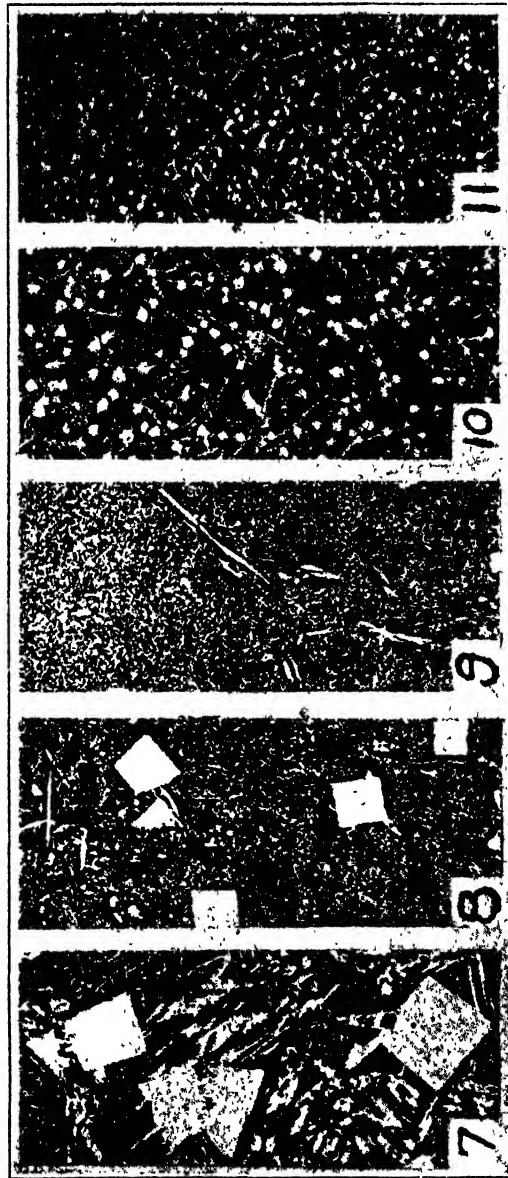


Fig. 7—Structure of an alloy containing approximately 82% tin, 10% antimony, and 8% copper. $\times 150$. This represents the average structure at the center of the ingot.
 Fig. 8—Structure of an alloy containing approximately 90% tin, 8% antimony, and 2% copper. $\times 150$. This represents the average structure toward the center of the ingot.
 Fig. 9—Same alloy as Fig. 8. This represents the average structure at the edge of the ingot. $\times 150$.
 Fig. 10—Alloy containing 89% tin, 8.7% antimony, and 2.3% copper. $\times 20$. Pouring temperature, 500°C.; mold temperature, 100°C. (Hudson and Darley).
 Fig. 11—Same alloy as in Fig. 10. $\times 20$. Pouring temperature, 300°C.; mold temperature, 100°C. (Hudson and Darley).

³See the remarks on the needle-shaped constituent in the article on the constitution of these alloys.

has an important effect on the dimensions of the cubes of SnSb, these decreasing in size as the rate of cooling is increased. The pouring temperature, except in so far as it affects the rate of cooling, is insignificant in its action in this regard.

In certain cases, however, the pouring temperature has quite an important effect upon the manner in which the needle-shaped constituent distributes itself. Hudson and Darley³ have shown in the case of an alloy containing 89.0% tin, 8.7% antimony, and 2.3% copper, poured at known temperatures into an iron ingot mold $1\frac{1}{2}$ in. long by $\frac{1}{2}$ in. wide by $\frac{1}{2}$ in. deep, previously heated to varying degrees, that (a) in those cases where the pouring temperature was above about 300°C., the primary needles separate from solution in the form of long,

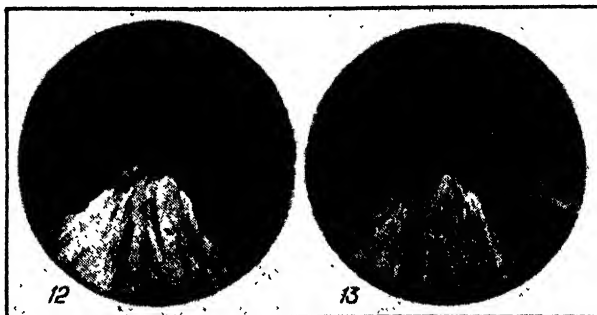


Fig. 12—Macrostructure of 3 $\frac{1}{4}$ % antimony-3 $\frac{1}{4}$ % copper alloy, as cast. Fig. 13—Same as Fig. 12, but annealed.

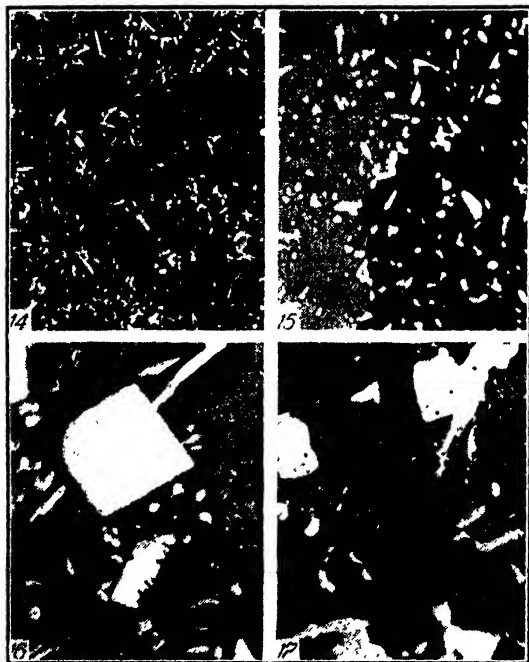


Fig. 14 and 15 same as Fig. 12 and 13 at 250X.
Fig. 16 and 17 same as Fig. 12 and 13 at 250X.

feathery or chain-like crystallites, generally arranged in a very distinct angular fashion and frequently in clearly defined triangular groups (Fig. 10); and (b) in those cases where the pouring temperature was about 300°C. or below, the needle-shaped constituent occurs chiefly as shorter and often much thicker needle shaped crystals or in star-shaped forms. Well marked triangular groups were rarely seen and the general "grain size" was much smaller (Fig. 11).

Hudson and Darley suggest that for each alloy of this system there will exist a critical temperature below which pouring should always be conducted if the triangular groupings of the crystallites of the needle shaped constituent are to be avoided, it being assumed that triangular groupings are objectionable on account of their effect on the properties of the alloy. To what extent, however, the results of experiments on relatively heavy sections can be applied to the thin linings ($\frac{1}{8}$ - $\frac{1}{4}$ in.) of white metal so widely used in engineering work is open to question. In general, pouring temperatures of from 400-450°C. do not appear to have a deleterious effect on the alloys of this system when cast in the form of thin linings.

Since bearing metals are used upon their structures has been deemed worthy of consideration. In this connection Homer and Plummer⁴ have studied two representative tin-antimony-copper alloys,

³O. F. Hudson and J. H. Darley, *Constitution and Structure of Certain Tin-Antimony-Copper Alloys*, *J. Inst. Metals*, 1920, v. 24, p. 361.

⁴O. E. Homer and H. Plummer, *Tech. Pub. of International Tin Research and Dev. Council*, Ser. A, No. 5, Aug., 1937.

samples of which were cut from cast rods $\frac{1}{2}$ in. in dia. The structures of these alloys (after polishing and etching) were photographed both before and after annealing at 165° C. for 1 week in a thermostatically controlled oven.

Fig. 12 and 13 show the macrostructure typical of the 3½% antimony-3½% copper alloy as cast and as annealed, respectively. These photographs support the view that any change in mechanical properties undergone by these alloys as a result of annealing is not due to a change in grain size.

Typical microstructures of this same alloy, as cast and as annealed, are shown in Fig. 14 and 15 at a magnification of 250 dia. The principal effects of annealing have been the coalescence of the particles of needle-shaped constituents and the effacement from the solid solution of the vague dark patches which are evidence of its inhomogeneity in the "as cast" state.

Photomicrographs, at a magnification of 500 dia., of typical sections of the 10% antimony-3½% copper alloy, as cast and as annealed, are shown in Fig. 16 and 17. Annealing this alloy causes the cubes of SnSb to spheroidize and numerous small particles of what appears to be SnSb to precipitate from the solid solution.

The effects of annealing upon the mechanical properties of these alloys are dealt with in the article on "Properties of Tin-Base Bearing Alloys."

Physical Constants of Tin

By Dr. C. L. Mantell*

Introduction—Tin metal having a purity as high as 99.9+% has long been available in the form of "Straits Tin," particularly those under the designations of Banka, Billiton, and Penang. Most of the properties of the metal have been determined on these grades of metal, a typical analysis of which is: Tin 99.950%, antimony 0.007, arsenic nil, lead trace, bismuth nil, copper 0.018, iron 0.045, silver nil, sulphur trace. Some of the recent work has been done on 99.99+ metal, particularly Chempur tin, a typical analysis of which is: Tin 99.9918%, antimony 0.0031, arsenic nil, lead 0.0025, bismuth 0.0004, copper 0.0004, iron 0.0016, silver nil, sulphur 0.0002, cobalt nil.

Small amounts of copper appreciably harden tin, while even traces of iron affect the color. With increasing purity the metal becomes appreciably more corrosion resistant to a number of electrolytes.

Allotropy of Tin—

Tin exists in a number of allotropic forms, shown diagrammatically in Fig. 1. At low temperatures the stable form is gray cubic or alpha tin, which changes at 18°C. to ordinary white tetragonal or beta tin. This suffers transposition at 161°C. to the so-called rhombic brittle or gamma tin, which at 232°C. passes into the molten state. Simson¹ states that according to his X-ray studies, gamma tin is hexagonal.

Ordinary tin changes into a gray powder when exposed to extremes of cold. Medallions, coins, and antiques in museums acquire a surface crust of powdery gray tin which gradually grows, seemingly self catalyzed, until disintegration results. This is the so-called "tin pest" or "disease" of the museums.

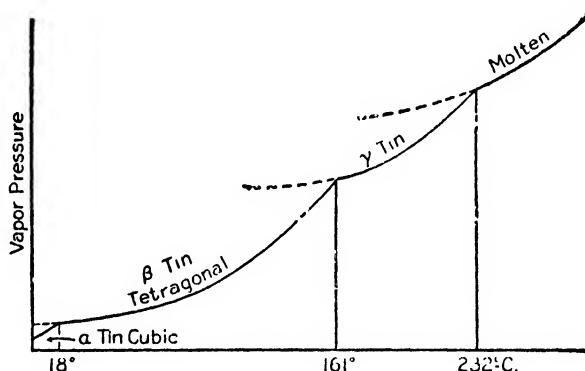


Fig. 1—Constitution of the allotropic forms of tin.

Table I
Atomic Properties

Atomic entropy		
White tin at 25°C.....	11.17 cal. per degree	Lewis, Gibson and Latimer ^a
Gray tin at 25°C.....	9.23 cal. per degree	Lewis, Gibson and Latimer ^a
Atomic heat		
White tin at		
22.4°K.	1.37	Lange ⁴
56.7°K.	4.06	
101.1°K.	5.40	
286.3°K.	6.27	
Gray tin at		
15.5°K.	0.599	Lange ⁴
31.5°K.	1.675	Lange ⁴
92.5°K.	4.42	Lange ⁴
283.7°K.	6.13	Lange ⁴
Atomic heat of fusion.....	1712 cal.	Richards ⁵
Atomic radius	1.40 Å	Pease ⁶
Atomic refraction	18.6-27.0	Gladstone ⁷

*Consulting Chemical Engineer, 360 Furman St., Brooklyn.

Atomic Weight—The element tin has the atomic No. 50. Its atomic weight is 118.70 according to the most recently determined and accepted values. According to Aston¹ there are 11 isotopes, which, arranged in order of relative abundance, have the following values: 120, 118, 116, 119, 117, 124, 122, 121, 112, 114, 115. Other atomic properties are given in Table I.

Crystal Form—Bijl and Kolkmeijer² show from their X-ray studies of gray tin that it crystallizes in the cubic system. Its space lattice is body-centered tetragonal with an edge of unit cube $a = 6.46$ Å units.

According to Polanyi and Schmid white tin crystallizes in a modified tetragonal lattice, containing in the unit cell four atoms of coordinates 000, $0\frac{1}{2}$, $\frac{1}{2}0$, and $\frac{1}{2}\frac{1}{2}$.

Color—The color of tin is white, with a slightly bluish tinge. Compared with tin, nickel is brown and chromium is definitely blue. Tin is whiter than silver or zinc. Exceedingly thin films of tin transmit various shades of brown when light is caused to pass through the film. The metal has a brilliant luster and when highly polished has high light reflectivity. The luster depends to a great extent upon the temperature at which the metal is poured when cast. If the temperature should be too high, iridescent colors may show on the surface as the result of oxide films. If the pouring temperature should be too low, the surface is dull. Small amounts of foreign metals such as lead, arsenic, antimony, and iron decrease the luster of tin and impart a yellowish tinge to the metal.

Density—Tin (purity 99.992%) has a density of 7.2984 g. per cc. at 15°C. in the cast condition. Values for the density (in g. per cc., or sp.gr.) for the different allotropic forms as well as in the molten condition are given in Table II.

Table II
Density Values

Specific gravity—		
White tin	7.2984	
Rhombic tin	6.53–6.56	
Gray tin	5.8466	
Molten at		
250°C.	5.983	Day, Sosman, Hostetter ³
300°C.	5.943	Day, Sosman, Hostetter ³
500°C.	5.814	Day, Sosman, Hostetter ³
700°C.	5.695	Day, Sosman, Hostetter ³
900°C.	5.578	Day, Sosman, Hostetter ³
1000°C.	5.518	Day, Sosman, Hostetter ³
1200°C.	5.399	Day, Sosman, Hostetter ³
1400°C.	5.280	Day, Sosman, Hostetter ³
1600°C.	5.162	Day, Sosman, Hostetter ³

Compressibility—The compressibility or percentage change in volume with unit change in pressure of 1 megabar (0.987 atmospheres; 14,504 psi.) of refined tin (99.99+) is given by Adams, Williamson and Johnston¹⁰ as 1.89×10^{-6} at 20°C. at atmospheric pressure, and 1.64×10^{-6} at 10,000 megabars pressure. Richards¹¹ gives a figure of 1.9×10^{-6} per megabar at 300 megabars pressure.

Thermal Expansivity—Data for the thermal expansion of tin is given in Table III for linear and cubic expansion coefficients.

Table III
Thermal Expansion

Linear expansion—		
–163–18°C.	0.000018	Cohen and Olie ¹²
White tin, 20–232°C.	0.000023–0.000024	Cohen and Olie ¹²
Gray tin, –163–18°C.	0.0000053	Cohen and Olie ¹²
Parallel to rotational axis of a single crystal at 20°C.	0.0000305	Bridgman ¹³
Perpendicular to rotational axis of a single crystal at 20°C.	0.00001545	Bridgman ¹³
Cubic expansion at—		
232–396°C.	0.0,106	Hogness ¹⁴
400–700°C.	0.0,105	Bornemann and Siebs ¹⁵
232–1600°C.	0.0,100	Day, Sosman and Hostetter ¹⁶

Freezing Point—The freezing point of pure tin (99.99+) is a pyrometric standardization point, the value of which is given for a Bureau of Standards "melting point" sample as 231.9°C. The melting point is raised by increase of pressure as shown in Table IV.

Table IV
Melting Points

Melting point	231.9°C.	National Bureau of Standards, 1919
Under 500 atmospheres.....	232.26°C.	Adams and Johnston ¹⁷
Under 750 atmospheres.....	233.09°C.	Adams and Johnston ¹⁷
Under 1000 atmospheres.....	233.89°C.	Adams and Johnston ¹⁷
Under 1490 atmospheres.....	235.47°C.	Adams and Johnston ¹⁷
Under 2000 atmospheres.....	237.18°C.	Adams and Johnston ¹⁷

Specific and Latent Heat—Specific Heat and latent heat of fusion are given in Table V.

Table V
Specific and Latent Heat

Specific heat—		
0–100°C.	0.055	Regnault ²¹
White tin at –193°C.	0.0390	Brönsted ¹⁸
Gray tin at –193°C.	0.0319	Brönsted ¹⁸
20°– –185°C.	0.0502	Richards and Jackson ¹⁹
–196°– –253°C.	0.0286	Dewar ²⁰
Molten tin at.....	0.0637	Spring ²²
250°–350°C.	0.0637	Person ²³
Heat of fusion.....	14.32 cal	International Critical Tables
	6.67 kilojoules per g atom	Glaser ²⁴

Boiling Point—Greenwood²⁵ and Mott²⁶ give the boiling point of tin as 2270°C., but the International Critical Tables place the value at 2260°C. The metal is non-volatile at ordinary melting, casting, and alloying temperatures. At temperatures around 1000°C. the vapor pressure is only 10⁻⁸ mm. mercury. According to the International Critical Tables, the latent heat of vaporization is 325 kilojoules per g. atom at the boiling point 2260°C. This is approximately 88,600 calories per mol (118.70 g.). The vapor pressure and related data are given in Table VI.

Table VI
Boiling Point and Vapor Pressure

Boiling point	2270°C.	Greenwood ²⁵ and Mott ²⁶
Vapor pressure, at:		
2005°C.	126 mm. Hg	Ruff and Mugdan ²⁷
2045°C.	178 mm. Hg	Ruff and Mugdan ²⁷
2160°C.	372 mm. Hg	Ruff and Mugdan ²⁷
2190°C.	485 mm. Hg	Ruff and Mugdan ²⁷
2195°C.	502 mm. Hg	Ruff and Mugdan ²⁷
2270°C.	755 mm. Hg	Ruff and Mugdan ²⁷
1970°C.	101 mm. Hg	Greenwood ²⁵
2100°C.	262 mm. Hg	Greenwood ²⁵
2270°C.	760 mm. Hg	Greenwood ²⁵
1010°C.	10 ⁻⁸ mm. Hg	Johnston ²⁸

Table VII
Thermal Conductivity

Thermal conductivity—		
Ag = 100.....	.313	Despretz ²⁹
–170°C.	0.195 absolute units	Lees ³⁰
15°C.	0.1828 absolute units	Kirchhoff and Hansemann ³¹
0°C.	0.1628 absolute units	Lorenz ³²
100°C.	0.1423 absolute units	Lorenz ³²
200°C.	0.145 absolute units	Jakob ³³
283°C.	0.081 absolute units	Könne ³⁴
417°C.	0.079 absolute units	Könne ³⁴
498°C.	0.078 absolute units	Könne ³⁴

Thermal Conductivity—The thermal conductivity of tin is low as compared to silver. Table VII gives absolute units (cal. per sec. per sq.cm. per cm. thickness per °C.) at various temperatures. A value of 0.15 absolute units is equivalent to 432 B.t.u. per hr. per sq.ft. per in. thickness per °F.

Fluidity—Fluidity is the reciprocal of viscosity which Sauerwald and Töpler⁴ studied for tin and obtained the figures in Table VIII.

Table VIII
Fluidity Data

Viscosity—		Viscosity—	
At 301°C.	0.01680	At 450°C.	0.01270
At 320°C.	0.01593	At 604°C.	0.01045
At 351°C.	0.01518	At 750°C.	0.00905

Optical Properties—The optical properties of tin have attracted attention from various workers. For the infra-red (10-12M) region, the reflecting power is high. The important optical properties are tabulated in Table IX.

Table IX
Optical Properties

Absorption coefficient for β -rays (M).....	M/D = 9.46	Crowther ³⁶
Absorption coefficient for γ -rays (M) from		
Radium	M/D = 0.281	Russell and Soddy ³⁷
Uranium	M/D = 0.341	Russell and Soddy ³⁷
Thorium-D	M/D = 0.236	Russell and Soddy ³⁷
Mesothorium	M/D = 0.305	Russell and Soddy ³⁷
Emissivity—		
Radiating capacity, tinned sheet iron (50°C.).....	0.04	
Tin, bright (50°C.).....	0.04	
Reflecting power—		
$\lambda = 1.0 \mu$	54%	Coblentz ³⁸
2.0μ	61%	
4.0μ	72%	
7.0μ	81%	Coblentz ³⁸
10.0μ	84%	
12.0μ	85%	Coblentz ³⁸
Refractive index for $\lambda = 589$ (sodium light).....	1.48	Drude ³⁹
Stopping power for α -rays.....	3.37	Bragg ⁴⁰

Electrical Resistivity—In comparison with silver, copper, and aluminum, tin is a poor conductor of electricity. The resistance increases with temperature, in reference to the solid and molten metal. Values are given in Table X.

Table X
Electrical Properties

Electrical conductivity		
Ag = 100	14.01	Becquerel ⁴¹
At — 183°C.	294,000 mhos	Dickson ⁴²
— 78°C.	114,000 mhos	Dickson ⁴²
0°C.	76,600 mhos	Dickson ⁴²
20°C.	86,900 mhos	International Critical Tables
91.45°C.	54,800 mhos	Dickson ⁴²
176°C.	42,300 mhos	Dickson ⁴²
Solid at melting point.....	44,900 mhos	Vassura ⁴³
Liquid at melting point.....	21,100 mhos	Vassura ⁴³
358°C.	18,800 mhos	Müller ⁴⁴
880°C.	15,400 mhos	Müller ⁴⁴
Electrical resistance (micro-ohms per cc.)		
20°C.	11.5	International Critical Tables
225°C.	22.00	Northrup and Suydam ⁴⁵
Just before fusion.....	22.00	
Just after fusion.....	47.40	
300°C.	49.44	Northrup and Suydam ⁴⁵
400°C.	52.00	
500°C.	54.62	
600°C.	57.22	
700°C.	59.88	
750°C.	61.22	Northrup and Suydam ⁴⁵
Solid at melting point.....	21.7	Schulze ⁴⁶
Liquid at melting point.....	47.8	Schulze ⁴⁶

Electrochemical Equivalent—Tin occurs as a bivalent and a tetravalent ion in the stannous and stannic forms. The values in various units for the electrochemical equivalent (defined as the number of g. deposited per sec. by a current of 1 ampere) are given in Table XI.

Table XI
Electrochemical Equivalents

Electrochemical Equivalents	Stannous II	Stannic IV	
Mg. per coulomb.....	0.61505	0.30752	Roush ⁴⁷
Coulomb per mg.....	1.62589	3.25178	Roush ⁴⁷
G., per ampere-hr.....	2.21417	1.10709	Roush ⁴⁷
Ampere-hr. per g.....	0.45164	0.90327	Roush ⁴⁷
Lb. per 1000 ampere-hr.....	4.88141	2.44070	Roush ⁴⁷
Ampere-hr. per lb.....	204.86	409.72	Roush ⁴⁷

Table XII
Mechanical Properties

Elastic limit	200 psi.	Coe ⁴⁸
Elastic modulus	4148 kg.-m. per sq. mm.	
Observed value	4170 kg.-m. per sq. mm.	Stuart ⁵¹
Calculated value	4130 kg.-m. per sq. mm.	Stuart ⁵¹
Hardness on		
Von Moh scale.....	1.8	Rydberg ⁵²
Brinell scale at 26°C. for:		
Cast (10 mm. ball, 1000 kg.).....	5.2	Coe ⁴⁸
Annealed at 100°C.....	5.0	Coe ⁴⁸
Internal pressure	68,700 megabars	Traube ⁵³
Plasticity number		
Copper = 49.3.....	3.5	Edwards and Herbert ⁵⁴
Poisson's ratio	0.33	
Pressure for critical plasticity,		
Cast tin	2160 psi	Coe ⁴⁸
Annealed at 100°C.....	2480-2780 psi	Coe ⁴⁸
Tensile strength	2000 psi.	

Table XIII
Physical Properties

Capillary constant		
247°C.	15.74 sq. mm.	
346°C.	15.77 sq. mm.	
398°C.	15.83 sq. mm.	
Critical pressure	650 atmospheres	Van Laar ⁵⁴
Critical temperature	3730°C.	Van Laar ⁵⁶
Diffusion coefficient (k) per sq.cm./day		
Sn into Hg at 10.7°C.....	1.53	Von Wogau ⁵⁷
Sn into Au at 500°C.....	4.65	Roberts-Austen ⁵⁸
Pb in Sn at 500°C.....	3.18	Roberts-Austen ⁵⁸
Heat of recrystallization		
For 50% deformation.....	6.5 cal.	Van Liempt ⁵⁹
For 100% deformation.....	13.0 cal.	Van Liempt ⁵⁹
Specific volume		
20°C.	0.1395	Hess ⁶⁰
409°C.	0.1462	Bornemann and Siebe ¹⁸
474°C.	0.1473	Bornemann and Siebe ¹⁸
523°C.	0.1479	Bornemann and Siebe ¹⁸
574°C.	0.1486	Bornemann and Siebe ¹⁸
602°C.	0.1490	Bornemann and Siebe ¹⁸
648°C.	0.1499	Bornemann and Siebe ¹⁸
Surface tension in hydrogen		
300°C.	526 dynes per cm.	Hogness ¹⁴
350°C.	522 dynes per cm.	Hogness ¹⁴
400°C.	518 dynes per cm.	Hogness ¹⁴
450°C.	514 dynes per cm.	Hogness ¹⁴
500°C.	510 dynes per cm.	Hogness ¹⁴
In vacuo at 247°C.....	539.8 dynes per cm.	
Trouton's constant	34.34	Van Liempt ⁶¹
Valency attraction	$\sqrt{A} = 38$	Van Laar ⁶²
Velocity of crystallization	90 mm. per min.	Czochralski ⁶³
Velocity of sound through tin.....	2640.4 m. per sec.	Masson ⁶⁴
Volume change on fusion and solidification		
Per cent at 232°C.	2.7	Bornemann and Siebe ¹⁸
		Endo ⁶⁵
		Toepler ⁶⁶

Electrolytic Solution Potential—According to the usual terminology, tin is electronegative to elements it replaces in solution and electropositive to those which displace it from solution. In simple solutions of sulphates, tin is electronegative to the precious elements, copper, hydrogen, and electropositive to elements like iron, aluminum, magnesium, zinc, and cadmium. In other than simple solutions, the position of tin may change, and it may be found to be electropositive to metals to which in sulphate solutions it acted in an electronegative manner. As to the corrosion of tin in coatings, no valid reasoning can be based on the electrochemical position of the metal in simple sulphate solutions. Reference should be made to extensive papers on this subject.⁴

Mechanical Properties—The tensile strength of tin is low and the pressure for critical plasticity is slightly above this value. Tin is readily extruded, drawn, stamped, and spun. It does not work harden appreciably. The elastic limit is low. Its hardness is low, decreasing with increase of temperature. High purity tin is extremely ductile and plastic. Small amounts of impurities, particularly lead, antimony, copper, iron, bismuth, and silver, harden the metal, increase its tensile strength and reduce ductility. Table XII contains values for a number of important properties.

Other Properties—Many major uses of tin as a coating or alloying metal depend on the wetting power, surface tension, contraction and expansion on freezing, diffusion and other physical properties which are listed in Table XIII.

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Properties of Tin-Base Bearing Alloys

By O. W. Ellis*

Introduction—The tin-base bearing metals, known commercially as "babbitt metals" or "babbitts", are essentially alloys of tin, antimony, and copper, to which as much as 30% of lead may be added—largely for the purpose of reducing their cost. Of the elements which materially improve these alloys cadmium is perhaps the most important; nickel is stated to be of value, but little definite information regarding its effects has so far been published.¹ Of elements to be avoided entirely, zinc and aluminum are the most important. Arsenic, bismuth, and iron should be limited in amount. The specifications of the A.S.T.M. (endorsed by the A.F.A.) and of the S.A.E. for white bearing metal alloys may be referred to in this connection.

In the former (A.S.T.M. Designation: B 23-26), paragraphs 4 and 5 read as follows:

4. The alloys shall conform to the following requirements as to chemical composition, within the limits specified in Section 5:

Alloy Grade* 'ON	Tin, %	Antimony, %	Lead, %	Copper, %	Iron, max., %	Arsenic, max., %	Zinc, %	Aluminum, %
1	91	4½	0.35 max.	4½	0.08	0.10	none	none
2	89	7½	0.35 max.	3½	0.08	0.10	none	none
3	83½	8½	0.35 max.	8½	0.08	0.10	none	none
4	75	12	10	3	0.08	0.15	none	none
5	65	15	18	2	0.08	0.15	none	none

*Grades Nos. 6-12, which represent lead-base bearing metals, have been omitted from this table to save space.

5. The following permissible variations in the percentages of the desired elements specified in Section 4 will be allowed, but shall not apply to the maximum percentages of impurities specified:

Percentage of Element Specified	Permissible Variations Over or Under the Specified Value. Units of Per Cent
Not over 2%.....	0.25
Over 2-5%, incl.....	0.50
Over 5-10%, incl.....	0.75
Over 10%	1.00

In the latter, the limits for the chemical compositions specified for metal in ingot form are closer than the limits specified for cast products, as allowances have been made for variations in the chemical content due to casting. The three S.A.E. specifications are as follows:

Specification No. 10, Babbitt

	Cast Products	Ingot
Tin, % min.....	90	90.75
Copper, %.....	4-5	4.25-4.75
Antimony, %.....	4-5	4.25-4.75
Lead, % max.....	0.35	0.35
Iron, % max.....	0.08	0.08
Arsenic, % max.....	0.10	0.10
Bismuth, % max.....	0.08	0.08
Zinc and aluminum.....	none	none

When finished bronze-backed bearings are purchased, a maximum of 0.6% lead is permissible in scraped samples provided a lead-tin solder has been used in bonding the bronze and the babbitt.

General Information—This babbitt is fluid and may be used for bronze-backed bearings, particularly for thin linings such as are used in aircraft engines. It is also suitable for die castings.

*Director of Metallurgical Research, Ontario Research Foundation, Toronto, Canada.

Specification No. 11, Babbitt

	Cast Products	Ingot
Tin, % min.....	86.00	87.25
Copper, %.....	5.00-6.50	5.50-6.00
Antimony, %.....	6.00-7.50	6.50-7.00
Lead, % max.....	0.35	0.35
Iron, % max.....	0.08	0.08
Arsenic, % max.....	0.10	0.10
Bismuth, % max.....	0.08	0.08
Zinc and aluminum...	none	none

When finished bronze-backed bearings are purchased a maximum of 0.6% lead is permissible in scraped samples provided a lead-tin solder has been used in bonding the bronze and the babbitt.

General Information—This is a rather hard babbitt which may be used for lining connecting rod and shaft bearings which are subjected to heavy pressures; its "wiping" tendency is slight. It is also suitable for die castings.

Specification No. 12, Babbitt

	Cast Products	Ingot
Antimony, %.....	9.50-11.50	10.25-10.75
Copper, %.....	2.25- 3.75	2.75- 3.25
Lead, % max.....	26.00	25.25
Tin, % min.....	59.50	60.00
Iron, % max.....	0.08	0.08
Bismuth, % max.....	0.08	0.08
Zinc and aluminum.....	none	none

General Information—This is a relatively cheap babbitt and is intended for bearings subjected to moderate pressures. It is also suitable for die castings.

Effects of Various Elements on Microstructure of Bearing Alloys—The presence of zinc and arsenic in bearing metals is looked upon with disfavor. According to Freeman and Brandt³ and Roast and Pascoe,⁴ arsenic increases the resistance of these alloys to deformation at all temperatures, while zinc has a similar effect at 100°F. but causes little or no change in their properties at room temperature.⁵ Zinc has been found to have a marked effect upon the microstructure of certain of these alloys,⁶ the cubes of SnSb tending to coalesce and form star-shaped groups. At the same time, though normally of a reddish hue, the alloys become white when as little as 0.032% of zinc is added.

Small quantities of aluminum (1%) modify the microstructure of these alloys, causing the cubes to disappear. Alloys containing aluminum have a fine, globular structure when rapidly solidified; but liquation occurs on slow freezing, the aluminum (in combination with a little copper and some antimony) tending to rise to the tops of castings during freezing.⁷

Bismuth is objectionable because it forms with tin a eutectic which melts at 137°C., so that at temperatures in excess of this its fusibility appreciably lowers the strength of alloys containing it.

In high tin alloys (such as A.S.T.M. Grades No. 1-3 and S.A.E. Specifications No. 10 and 11) lead is limited to 0.35%. This is because of the deleterious effect of lead upon the strength of these alloys at high temperatures (150°C. or more). Lead forms with tin a eutectic which melts at 183°C. Bearings which exceed this temperature naturally become fragile because of the formation within them of a liquid phase.

Cadmium is without appreciable effect on the structures of these alloys if lead be absent. In alloys free from lead a constituent, probably a eutectic, appears when the cadmium content reaches about 3% in a bearing metal containing 7% antimony and 3.5% copper. Increase in the antimony content appears to admit of more cadmium being retained in solid solution; on this account the fusible constituent, which melts at about 170°C., is prevented from appearing. Conversely, a reduction in antimony causes the eutectic to appear at a lower cadmium content.⁸ When lead is present, it forms with cadmium and tin a ternary eutectic which melts at 145°C. Bearings, therefore, cannot be operated at temperatures in excess of this point without danger of "wiping" and serious loss of strength.

Mechanical Properties at Room Temperature—Grades No. 1-5 of the above A.S.T.M. Designation: B 23-26 have been intensively investigated by Freeman and Woodward.¹ The main results of their work are given in Table I.

Table I
Composition and Physical Properties¹ of White Metal Bearing Alloys

Alloy No.	—Specified Composition— of Alloys, %				Sp.gr.	—Compositions of Alloys— Tested, %				—Yield— Point, psi. ²	
	Cu	Sn	Sb	Pb		Cu	Sn	Sb	Pb	20°C.	100°C.
1	4.5	91.0	4.5	....	7.34	4.56	90.9	4.52	none	4,400	2,650
2	3.5	89.0	7.5	....	7.32	3.1	89.2	7.4	0.03	6,100	3,000
3	8½	83½	8½	....	7.46	8.3	83.4	8.2	0.03	6,600	3,150
4	3.0	75.0	12.0	10.0	7.52	3.0	75.0	11.6	10.2	5,550	2,150
5	2.0	65.0	15.0	18.0	7.75	2.0	65.5	14.1	18.2	5,050	2,150

Alloy No.	Johnson's Apparent Elastic Limit, psi. ³		Ultimate Strength, psi. ⁴		Brinell Hardness ⁵		Melting Point		Temp. of Complete Liquefaction		Proper Pouring Temp.	
	20°C.	100°C.	20°C.	100°C.	20°C.	100°C.	°F.	°C.	°F.	°C.	°F.	°C.
1	2,450	1,050	12,850	6,950	170	80	433	223	...	...	825	441
2	3,350	1,100	14,900	8,700	24.5	12.0	466	241	669	354	795	424
3	5,350	1,300	17,600	9,900	27.0	14.5	464	240	792	422	915	491
4	3,200	1,550	16,150	6,900	24.5	12.0	363	184	583	306	710	377
5	3,750	1,500	15,050	6,750	22.5	10.0	358	181	565	296	690	366

¹The compression test specimens were cylinders 1½ in. in length and ½ in. dia., machined from chill castings 2 in. in length and ¾ in. in dia. The Brinell tests were made on the bottom face of parallel machined specimens cast in a 2 in. dia. by ¾ in. deep steel mold at room temperature.

²The values for yield point were taken from stress-strain curves at a deformation of 0.125% reduction of gage length.

³Johnson's apparent elastic limit is taken as the unit stress at the point where the slope of the tangent to the curve is 1½ times its slope at the origin.

⁴The ultimate strength values were taken as the unit load necessary to produce a deformation of 25% of the length of the specimen.

⁵These values are the average Brinell number of three impressions on each alloy, using a 10 mm. ball and a 500 kg. load applied for 30 sec.

Table II
Brinell Hardness Numbers, Ultimate Strength, Limits of Proportionality, and Yield Points of Tin-Base Bearing Metals

Antimony, %		Copper, %				
		0.5	1	2	4	8
2	Hardness	9.5	11.3	12.3	13.0	15.3
	Ultimate strength, psi.	7,560	8,540	8,880	10,000	12,080
	Proportional limit, psi.	1,580	1,590	1,960	1,860	2,200
	Yield point, psi.	4,380	5,160	5,880	6,580	7,220
4	Hardness	12.1	14.7	15.0	16.7	20.8
	Ultimate strength, psi.	9,360	10,680	10,920	12,030	13,800
	Proportional limit, psi.	2,355	2,490	2,450	2,890	3,155
	Yield point, psi.	5,660	7,080	7,060	8,300	10,840
6	Hardness	14.6	17.0	19.2	19.5	26.6
	Ultimate strength, psi.	11,500	12,880	13,480	14,040	16,400
	Proportional limit, psi.	3,390	3,140	3,380	3,540	4,795
	Yield point, psi.	7,100	7,500	8,800	9,700	12,660
8	Hardness	18.6	19.9	21.7	21.9	26.1
	Ultimate strength, psi.	13,960	14,260	15,180	15,860	16,880
	Proportional limit, psi.	3,230	3,608	3,790	4,530	4,970
	Yield point, psi.	8,640	8,860	9,920	11,340	13,480
10	Hardness	18.7	20.8	20.8	22.6	30.4
	Ultimate strength, psi.	13,840	14,000	14,420	16,040	18,420
	Proportional limit, psi.	3,560	3,630	4,460	4,880	5,670
	Yield point, psi.	8,240	9,440	9,780	11,920	14,580

Values for Brinell hardness numbers, limits of proportionality, and yield points in compression, and compressive strengths (loads per unit initial area required to compress test pieces 0.250 in. per in. length) of representative alloys of the tin-antimony-copper system are given in Table II taken from Ellis and Kareltz,⁸ to whose paper reference should be made for details.

A most important point brought out by Freeman and his collaborators was that the total deformation of the sample in the compression testing of babbitts is a function of the time of application of the load—a point sometimes overlooked by those reporting and studying results of tests on materials as plastic as are these alloys. What is true of the compression test is true also of other types of static tests.⁹ However, the known limitations of static tests do not discount their value. A Brinell test, for example, wherein the load is applied for a standard time (say, 30 sec.) is of considerable value for purposes of manufacturing control.

The properties in tension at room temperature of a number of tin-base bearing metals have been investigated by Munday, Bissett, and Cartland,¹⁰ Boegehold and Johnson,¹¹ Arrowsmith,¹² von Göler and Sachs,¹³ and others. The curves (Fig. 1a and 1b) are from Arrowsmith, whose tests were conducted on unmachined gravity die cast samples 0.226 in. in dia. with a gage length of 0.884 in. The samples were broken approximately 1 hr. after being cast. The rate of straining in these tests was about 0.017 in. per min.

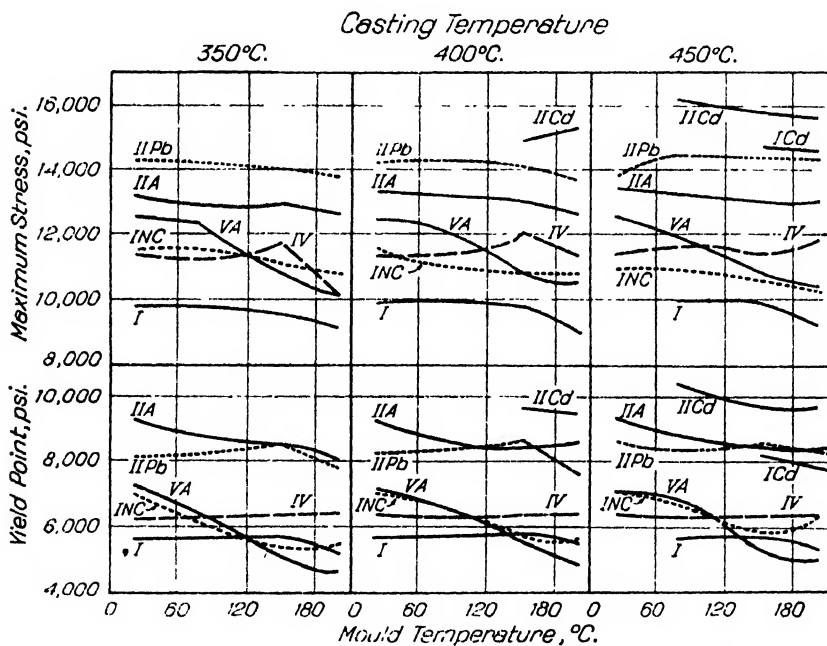


Fig. 1a—Effect of cadmium on the properties of tin-base bearing metals.
(See Table IIA for meaning of symbols on curves).

The relationship between the properties of the tin-base bearing metals in compression and their Brinell hardness numbers is close enough to permit a fair estimate to be made of their properties in compression. Further, a relationship seems to exist between the endurance limits, tensile strengths, and Brinell hardness numbers of these alloys. Macnaughtan¹⁴ believes "that for exploratory purposes the Brinell hardness and tensile tests may prove to be a useful guide to the fatigue-resisting properties" of such materials.

Repeated blow drop tests¹⁵ and single blow drop tests¹⁶ on bearing metals have been the subject of considerable investigation. In the writer's opinion such tests, while of interest, serve no better than do Brinell hardness and tensile tests to assess the relative usefulness of these alloys in service. Reference should be

made to the original papers for information regarding the malleability of individual mixtures.

The endurance limit (20,000,000 cycles) of a $3\frac{1}{2}\pm\%$ copper-tin-base bearing metal (0.25% lead, 0.03% arsenic, trace of iron) poured at 350°C. into a mold at 150°C. increases from about 3,400 psi. with 3% antimony to about 4,400 psi. with 6% antimony, and to about 4,800 psi. with 9% antimony. Concurrently, the tensile strength (straining rate, 1.2 in. per sec.) increases from about 7,800 psi. to about 11,200 psi. and about 13,500 psi., respectively, while the Brinell hardness number (125 kg. load; 10 mm. ball; 30 sec.) rises from 15 to about 21 and about 26, respectively.¹⁴

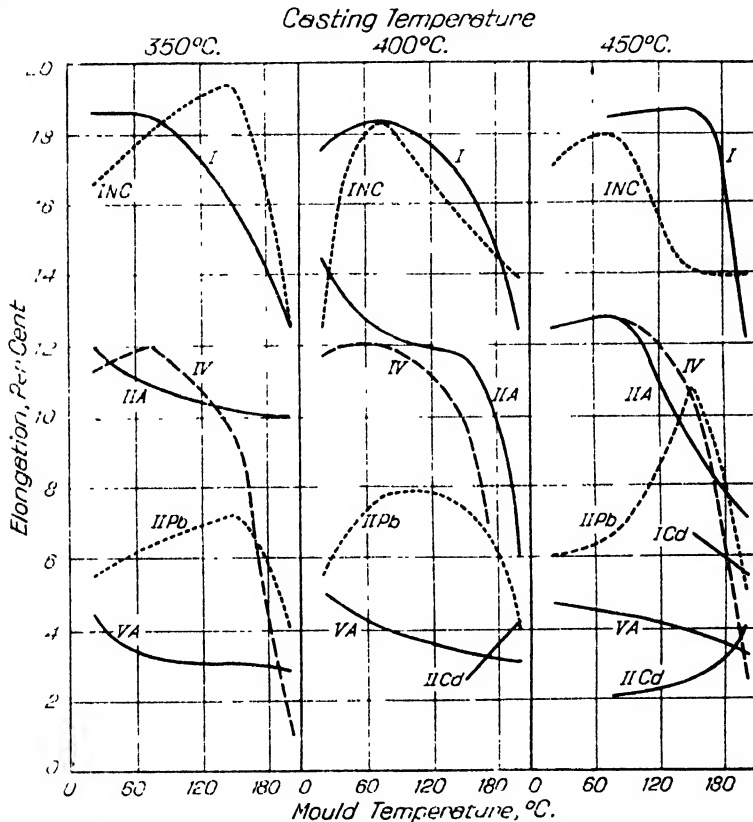


Fig. 1b—Effect of cadmium on the properties of tin-base bearing metals
(See Table IIA for meaning of symbols on curves).

The impact resistance of tin-base bearing metals closely resembling A.S.T.M. Grades No. 1 and 3 has been measured by Herschman and Basil¹⁷ with the following results:

Alloy Grade No.	Izod Impact Numbers (ft.-lb.)				
	20°C.	60°C.	100°C.	150°C.	200°C.
1	$2\frac{1}{2}$	N. O.	3	$3\frac{1}{2}$	$2\frac{1}{2}$
3	$\frac{3}{4}$	1	1	$1\frac{1}{2}$	$1\frac{1}{2}$

The results of experiments by Karelitz and Ellis¹⁸ on the rolling of tin-base babbitts show the extent to which these alloys can resist plastic deformation without rupture. Carefully machined samples, $1\frac{1}{2}$ in. long, 1 in. wide, and $\frac{1}{8}$ in. thick, were given 13 passes through highly polished, 6 in. dia. rolls, the reduction in thickness per pass being 0.025 in. The final thickness of the samples was therefore 0.175 in.

No attempt was made to trim the samples when signs of cracking were observed. The results of the experiments are shown in the following table:

Sample No.	Cu (%)	Sb (%)	Condition After Rolling	Sample No.	Cu (%)	Sb (%)	Condition After Rolling
1	0.5	2	No cracks	14	2	8	Few large cracks
2	0.5	4	No cracks	15	2	10	Large deep cracks
3	0.5	6	No cracks	16	4	2	No cracks
4	0.5	8	Small cracks	17	4	4	No cracks
5	0.5	10	Few large cracks	18	4	6	Small cracks
6	1	2	No cracks	19	4	8	Large cracks
7	1	4	No cracks	20	4	10	Large cracks
8	1	6	No cracks	21	8	2	Very few cracks
9	1	8	Few large cracks	22	8	4	Very few cracks
10	1	10	Few large cracks	23	8	6	Few large cracks
11	2	2	No cracks	24	8	8	Large deep cracks
12	2	4	No cracks	25	8	10	Broken
13	2	6	No cracks				

Sample 25 showed definite signs of cracking after the second pass, samples 10, 14, 15, 19, and 20 after the fourth pass. Sample 25 failed completely during the twelfth pass.

Herschman and Basil¹¹ also conducted wear tests on these alloys, using a modified Amsler test in which a steel wheel (Brinell hardness number, about 240) rolled in circumferential contact with a bronze wheel fitted with a babbitt tire. A load of 5 lb. was placed on the steel wheel during test. A stream of kerosene was directed onto the babbitt near its area of contact with the steel. The losses of weight per 1,000 revolutions of Grades No. 1 and 3 were about the same and were definitely lower than those of Grades No. 6, 7, 8, 10, and 11, an alkaline earth metal "hardened lead," an 82/18 cadmium-zinc alloy, and a modified Grade No. 8 alloy containing 1.0% copper, 0.6% arsenic, 0.2% cadmium, and 0.2% nickel in place of part of the tin. The last alloy was the best of the latter group (that is, No. 6, 7, 8, 10 and 11 and the others noted); it had lost 0.6 g. after 50,000 revolutions as compared with 0.2 g. for Grades No. 1 and 3. Service tests on crankshaft bearings made of Grade No. 1 alloy, "hardened lead," Grade No. 10 alloy, and a 90/10 tin-copper alloy frequently used in U. S. Army truck motors showed that "the tin-base alloys were superior in their resistance to both the 'hardened lead,' and lead-antimony-tin alloy containing about 3% tin."

The results may here be noted of tests made by Jakeman and Barr¹² on behalf of the Tin Research Subcommittee of the British Nonferrous Metals Research Association with the primary object of ascertaining the comparative chemical action of lubricants upon tin-base and lead-base bearing metals. They found that under their conditions of test (using a journal friction testing machine with bearings fully lubricated by continuous circulation of oil) there was no marked chemical reaction between lubricants and alloys except where oils containing free fatty acid were used with alloys containing high percentages of lead. The tests also showed that, generally speaking, bearings made of high lead alloys showed greater frictional losses and wear than those made of high tin alloys.

Effects of Cadmium on Mechanical Properties of Tin-Base Bearing Metals—In Fig. 1a and 1b reference is made to alloys containing 1% of cadmium. These alloys merit attention. By interpolation of curves published by Macnaughtan¹³ the information given in Table III has been obtained.

Table IIA

Ref. No.	Tin	Antimony	Lead	Copper	Iron	Arsenic
I	92.3	3.78	0.30	3.85	0.04	0.03
INC	88.8	7.14	0.28	3.74	trace	0.03
ICd			No. I plus 1% cadmium			
IIA	85.0	10.75	0.30	3.90	0.04	trace
IIcd*	85.5	9.88	0.33	4.21	0.08	0.03
IIIf†	85.5	9.88	0.33	4.21	0.06	0.03
	81.7	10.10	4.10	3.99	0.07	0.06
IV	39.3	10.50	48.60	1.83	0.04	0.06
VA	8.40	14.60	79.10	0.04	trace	0.06

*Plus 1.0% cadmium. †Plus 4% lead.

Table III
Effects of Cadmium (1%) on Hardness and Strength of Tin-Base Bearing Metals
(Copper, 3½%; Lead, 0.04%)

Antimony, %	Cadmium, %	Tensile Strength, psi.	Brinell Hardness No.
4	{ Nil	9,200	17½
	{ 1	10,000	25
6	{ Nil	11,000	21
	{ 1	13,800	26
8	{ Nil	13,400	24
	{ 1	14,700	30½
10	{ Nil	13,800	26
	{ 1	15,900	32
12	{ Nil	14,400	27
	{ 1	16,900	33

The results of work by Haigh on an alloy containing 3½ copper and 7% antimony indicate that 1% cadmium increases its endurance limit at room temperature from about 4,600 psi. to about 5,500 psi. on the basis of 20,000,000 reversals of stress. Von Göler and Sachs" state that the hot strength of these alloys is "markedly increased at temperature up to 180° . . . The running properties are favorably influenced by the addition of cadmium. From the aspect of foundry technique these alloys . . . do not exhibit any peculiarities as compared with the usual high tin white metals."

Behavior of Alloys at High Temperatures—The behavior of tin-base bearing metals at high temperatures is considerably affected by small changes in composition. Bismuth and lead are objectionable on account of the fusibility of the eutectics which these metals form with tin. Opinions differ, though unimportantly, as to the effect of lead upon the mechanical properties of these alloys at high temperatures. Without doubt lead somewhat increases the strength and hardness of tin-base bearing metals at room temperature.* This effect, however, is almost entirely lost in A.S.T.M. Grades No. 1, 2 and 3 at temperatures between 90°C. and 125°C. Boegehold and Johnson" quote the following values for the compressive flow points, the tensile strengths, and the percentage elongations at 204°C. of a series of tin-base bearing metals containing about 7½% antimony and 7½% copper.

	Sn %	Sb %	Cu %	Pb %	Bi %	Compressive Flow Point, psi.	Tensile Strength, psi.	Elongation in 2 in., %
No. 1.....	82.87	7.51	7.55	1.97	...	260	.....	.....
No. 2.....	84.26	7.80	7.94	trace	...	500	.....	.....
No. 3.....	82.50	7.50	7.50	2.00	0.5	190	.....	.....
No. 4.....	85.0	7.50	7.50	0	...	1570-1630	.....	116.0
No. 5.....	83.0	7.50	7.50	2.0	...	470- 510	.....	1.0

These results indicate that little is to be gained by introducing lead into high tin alloys for the mere purpose of increasing their resistance to deformation, save where the temperatures of the bearings will not exceed about 90°C.

The importance of cadmium as a strengthener of tin-base bearing metals cannot be lightly dismissed. The behavior of a number of such alloys at elevated temperatures has been the subject of work by Greenwood" and by Homer and Plummer.

Of these workers, the first investigated the tensile properties of cast strips of white metal, 6 in. long, ¼ in. wide, and ¼ in. thick, with a reduced section ¼ in. wide and 0.7 in. long in the center. The percentage elongation of these pieces was determined on a gage length of 0.7 in. (equivalent to 4√A where A equals the original area of the test sample). The results of Greenwood's tests are quoted in Table IV:

*Grant" has remarked: "No failures that could be attributed to lead have been observed, although as much as 6 or 7% lead has not infrequently been found in bearings subjected to severe usage." This is a point of some importance. The fact that alloys such as A.S.T.M. Grades No. 4 and 5 and S.A.E. Specification No. 12, Babbitt, find extensive use fully confirms Grant's observation. However, to use such alloys in the form of thin linings for automotive and aircraft bearings is quite impracticable, not only on account of difficulties of assembly, but also because of their known failure to meet service requirements.

The yield points in the tables below were calculated from the loads at which measurable flow first occurred in the time interval (about 8 sec.) which elapsed

between successive readings of strain.

Greenwood's results show that as the temperature of test rises, the yield points and tensile strengths of most bearing metals fall fairly uniformly, while the percentage elongations and reductions of area increase. However, the ductility temperature curves are less regular than the stress temperature curves. In all the cases examined by Greenwood the temperature coefficient of ductility was greater from 100-175°C. than from room temperature to 100°C.

Homer and Plummer⁴ considered the effect of temperature upon the mechanical properties of test samples most of which had been annealed at 165°C. for one

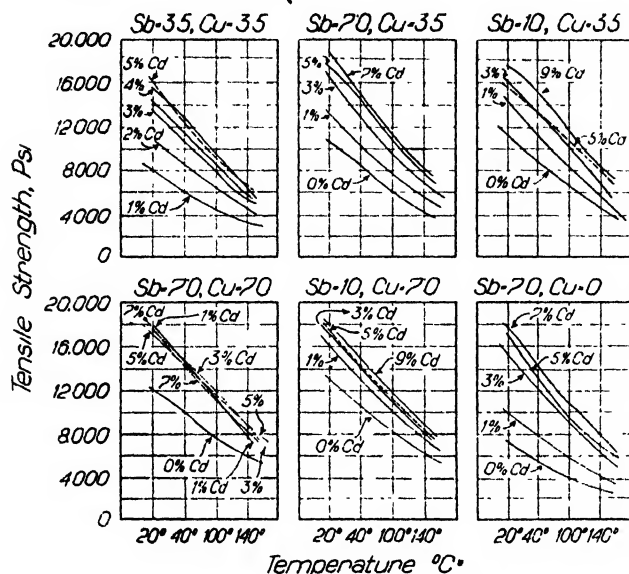


Fig. 2—Strength temperature curves for tin-base bearing alloys.

week. Some of the alloys containing large amounts of cadmium were treated at 158°C. for 10 days, or at 150°C. for 2 weeks, because they tended to soften and bend at the highest annealing temperature. The object of annealing was to alter the mechanical properties of the alloys from those of the materials as cast to those

Table IV
Tensile Properties of White Metal Bearing Alloys at Elevated Temperatures

	Test Temp., °C.	Maximum Stress, psi.	Yield Point, psi.	Elongation (% on 4√A)	Reduction Area, %
ALLOY 1.*	18	8,500	6,800	20.5	24
Cast. Temp., 450°C.....	50	7,200	5,700	26	34
Mold Temp., 20°C.....	100	4,760	3,900	25	35
	150	3,400	2,320	32	38
	175	2,400	1,400	36	41
ALLOY 1 NC.*	20	10,040	7,300	18.5	25
Cast. Temp., 400°C.....	50	8,200	5,900	24	27
Mold Temp., 20°C.....	100	5,800	4,300	23	28
	150	3,600	2,300	32	38
	175	2,600	1,400	38	44
ALLOY 1 Cd.*	18	12,900	10,000	8.5	10
Cast. Temp., 550°C.....	50	9,800	7,200	16	19
Mold Temp., 20°C.....	100	6,900	5,100	20	26
	150	3,860	2,600	45	40
	175	2,640	1,740	63	69
ALLOY 2.*	18	11,800	9,400	13	17
Cast. Temp., 450°C.....	50	9,940	7,700	17	25
Mold Temp., 20°C.....	100	7,200	5,500	23	28
	150	4,360	3,480	33	43
	175	2,780	2,240	52	61
ALLOY 2 Pb.*	20	12,400	8,800	10	12
Cast. Temp., 450°C.....	50	9,100	6,300	13	17
Mold Temp., 20°C.....	100	5,800	4,500	18	23
	150	3,100	2,000	21	36
	175	1,980	1,100	33	46

(Continued)

	Test Temp., °C.	Maximum Stress, psi.	Yield Point, psi.	Elongation (% on $\frac{1}{4}A$)	Reduction Area, %
ALLOY 2 Cd.*	18	14,500	11,600	8	10
Cast. Temp., 550°C.....	50	11,800	8,900	13	14
Mold Temp., 20°C.....	100	7,100	5,700	23	28
	150	4,500	2,300	29	35
	175	3,600	1,740	45	42

*Compositions of the Above Alloys	Alloy No.	Sn	Sb	Pb	Cu	Fe	As
	1	92.3	3.78	0.30	3.55	0.04	0.03
	1 NC	88.8	7.14	0.47	3.21	0.03	trace
	1 Cd	No. 1 + 1% Cd					
	2	85.5	9.88	0.33	4.21	0.05	0.03
	2 Pb	No. 2 + 4% Pb					
	2 Cd	No. 2 + 1% Cd					

which the alloys might be expected to possess after they had been in service for a time sufficient to bring them to structural equilibrium.

The test pieces used were cast to shape, 0.226 in. dia. and 0.884 in. long between the shoulders. Results of the more important tests are shown graphically in Fig. 2. Each graph gives the strength temperature curves obtained from a group of alloys of similar composition. Since frequently two or more alloys in a group have similar properties and the curves are on this account liable to become confused, a different zero on the temperature axis has been used for each curve in each group. In this way the various curves plotted in each figure are spaced out laterally from one another, although they are all drawn to the same scale.

The values for percentage elongation were determined in all cases but, not being concordant, are unsuitable for graphical representation. A general increase in ductility with temperature occurred in all cases, though the increase was slight in some. Above 120°C. some of the high cadmium alloys showed relatively high ductility, while their percentage elongation was small at lower temperatures. Up to 120°C., however, the increase in elongation with temperature was gradual and normal in all cases. The original paper should be consulted for information regarding the Brinell hardness numbers of these alloys at various temperatures and the range of percentage elongation.

Homer and Plummer conclude that the addition of cadmium increases the strength and hardness of the tin-antimony-copper alloys. On the whole, there is a continuous increase of strength with increasing cadmium content, but the extent of the increase becomes progressively less. In most instances there is not much advantage to be gained by adding more than 3% cadmium, particularly as the ductility of the alloys diminishes as their strength increases. It is of particular interest to note that nearly all the alloys lose about the same proportion of their tensile strength on heating through the same range of temperature.

Work must still be done on the effect of copper on the strength of tin-base bearing metals at high temperatures. A consensus of opinion supports the view that increase in copper beyond about 3½% lowers their resistance to certain types of severe service, even though copper does increase both hardness and strength in these alloys. The remarkable behavior, for example, of A.S.T.M. Grade No. 1 in the form of linings (0.02-0.03 in. thick) for connecting rod and crankshaft bearings of automobile and aircraft engines has yet to be logically explained. In this connection it may be noted that "the compressive stress required to cause . . . plastic flow is raised as the ratio of the initial area under compression to the thickness of the metal is increased,"²² an effect that is nicely shown in the following table:

Area and Form of Cross Section of Test Sample, in.	Apparent Limit of Proportionality Under Compression, psi.
$\frac{1}{4} \times \frac{1}{4}$	1,800
$\frac{1}{2} \times \frac{1}{2}$	3,000
1 x 1	3,200

While these results refer to lead, their importance in explaining the increase in strength due to reducing the thickness of babbit in bearings should not be underestimated.

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Preparation and Etching of Tin and Tin Alloys for Metallographic Examination

By C. H. Hack*

The preparation of tin and its alloys for metallographic examination requires good technique and care because of the softness and ease of formation of flowed metal on the surface of the specimens. In general, the procedure in preparation is identical to that outlined on page 1556 for lead and lead alloys. The harder alloys are more easily prepared than the softer ones.

The initial surfacing of the specimens may be done by filing or machining on a lathe, using a sharp tool having a sharp rake, followed by grinding on emery papers of decreasing fineness. If a microtome is available, it may be used advantageously in minimizing the amount of subsequent polishing. However, if a microtome is used, a check should be made to see that it possesses three requisite properties as outlined by Vilella, namely: Sufficient rigidity, a properly sharpened knife and such adjustments that cuts of 2 microns in thickness may be made. If a microtome is not available, good success may be had by attaching a microtome knife to the front end of the supporting arm of a milling machine. The specimen is clamped in a vise attached to a slide rest (similar to the type used for a lathe)

Etching Reagents for Tin and Its Alloys

Etching Reagent	Composition	Remarks	Use
No. 1 Nitral	$\{ \text{HNO}_3 \quad 2-5 \text{ ml.}$ $\quad \text{C}_2\text{H}_5\text{OH} \quad 95-98 \text{ ml.}$	Swab or immerse for several minutes	Tin-cadmium or tin-iron alloys
No. 2 Potassium dichromate	Acidified dilute solution		Tin-cadmium alloys
No. 3 Mixed acids in glycerol ¹	A. $\{ \text{HNO}_3 \quad 1 \text{ part}$ $\quad \text{HCl} \quad 1 \text{ part}$ $\quad \text{Glycerol} \quad 8 \text{ parts}$	Immerse $\frac{1}{2}$ -10 min. at 38-42°C.	A. Tin-lead alloys
	B. $\{ \text{HNO}_3 \quad 1 \text{ part}$ $\quad \text{HCl} \quad 3 \text{ parts}$ $\quad \text{Glycerol} \quad 5 \text{ parts}$	Same as for A, above	B. Pure tin
No. 4 Hydrochloric acid	A. HCl (conc)	Immerse for several seconds	To remove surface flow
	B. $\{ \text{HCl} \quad 10-20 \text{ ml.}$ $\quad \text{H}_2\text{O} \quad 90-80 \text{ ml.}$	Immerse $\frac{1}{2}$ -5 min. following A.	Follow A
	C. $\{ \text{HCl} \quad 10 \text{ ml.}$ $\quad \text{H}_2\text{O} \quad 90 \text{ ml.}$	Electrolytic etch at low current density	Tin-iron alloys
No. 5 Ferric chloride	$\{ \text{FeCl}_3 \quad 10 \text{ g.}$ $\quad \text{HCl} \quad 2 \text{ ml.}$ $\quad \text{H}_2\text{O} \quad 95 \text{ ml.}$	Immerse $\frac{1}{2}$ -5 min. at room temperature	Microetching tin-rich Babbitt metal
No. 6 Nitric acid ²	$\{ \text{HNO}_3 \quad 5 \text{ ml.}$ $\quad \text{C}_2\text{H}_5\text{OH (abs)} \quad 95 \text{ ml.}$		Pure tin
No. 7 Picric acid and nitric acid ²	Alcoholic solution		Tin-iron alloys
No. 8 Ammonium polysulphide ³	Concentrated solutions	Immerse 20-30 min. at room temperature	Macroetching of tin-rich babbitt metals
No. 9 Ammonium Persulphate	$\{ (\text{NH}_4)_2\text{S}_2\text{O}_8 \quad 5 \text{ ml.}$ $\quad \text{H}_2\text{O} \quad 95 \text{ ml.}$	Blackens out the tin or tin alloy, leaving the compound as a bright contrasting layer	Tin coatings on steel
No. 10 Acetic Acid	$\{ \text{HC}_2\text{H}_3\text{O}_2 \quad 50 \text{ ml.}$		
	$\quad \text{H}_2\text{O} \quad 50 \text{ ml.}$		
	$\quad \text{H}_2\text{O}_2 \quad 1 \text{ drop}$		soldered joint

Note—Solutions of silver nitrate or 10% nitric acid plus 5% chromic acid are also occasionally used.

mounted to the moving bed plate at a slightly inclined angle. Settings for thin cuts as small as 1 micron may then be made by turning the screw of the slide rest. A final microtoming with cuts from 1-2 microns is preferable for tin and its alloys.

When preparing thin sections, such as tin coatings on metals or thin sections of babbitt linings for metallographic examination, it is generally necessary to mount the section in some molding medium. Wavy materials sometimes used, have a dis-

*National Lead Co., Brooklyn.

advantage, in that they clog the polishing papers and soften in alcoholic etching agents or by solvents used for drying. Likewise, fusible alloys used for mounting, clog the polishing papers, and are usually attacked more readily than the specimen by the etching reagent. 'Acid-hardened bakelite has recently been used for mounting with good success.' The procedure for using this is to add 10 cc. of a bakelite acid-hardening solution to 100 cc. of the bakelite resin, mixing thoroughly. The mixture is then poured into the mold containing the specimen and heated to 40-45°C. when the bakelite begins to harden. It is then further heated at 60°C. for 1-1½ hr. when it sets hard. Bubbling and too rapid hardening may take place if too high a temperature is applied, therefore, it is desirable to use the lower temperature (40°C.) for setting the resin, followed by the application of a higher temperature (60°C.) for hardening. Only sufficient material should be mixed for the immediate work, as the mixture hardens on aging at room temperature. One of the advantages of the acid hardened bakelite is that it does not require high temperatures and pressures.

Polishing—If the specimen has only been given a lathe cut finish, the polishing should start with No. "0" emery paper, followed by successive polishing on No. "00", No. "000" emery paper, all lubricated with paraffin dissolved in kerosene (100 g. of paraffin in 200 ml. kerosene). After polishing on each paper, the specimen should be washed in warm kerosene to remove the grit and paraffin, followed by washing with soap and water to remove the kerosene.³ The specimen may then be etched with HCl (10-20%) or any other suitable etching reagent to remove any metal that may have flowed on the polished surface.⁴ If the specimen has been finished by microtoming, the specimen may be polished on No. "000" emery paper to remove any scratches left by the microtome blade.

In either case, the specimen is then polished on a rotating wheel covered with broadcloth, using a soap solution of levigated alundum grain* (size 600 grain). The solution of soap and levigated alundum grain may be prepared as follows: 5 g. of alundum grain is added to 300 ml. of water. This mixture is thoroughly agitated and allowed to stand for 15 min., when the supernatant suspension is decanted. To this decanted suspension 40 g. of soap are added and the mixture heated until the soap dissolves. As this mixture is nearly solid at room temperature, it is necessary to use it warm. When this polishing medium is poured on to the polishing wheel it forms a gelatinous mass, viscous enough so that it is not thrown off the wheel when driven at 120 r.p.m.⁵ The final steps of preparation consist in polishing on a good grade of silk velvet, using the above polishing medium followed by etching, with subsequent alternate polishings and etchings until the true structure is revealed.¹

Success has been obtained by microtoming, followed by etching rather deeply and then polishing on a polishing wheel covered with silk velvet, using magnesium oxide and water without addition of soap. The specimen is then washed thoroughly in running water, etched and dried. Further light polishings and etchings may be made if necessary. This method has been found to be satisfactory and saves a good deal of time in polishing.

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*Finer abrasives such as alumina or magnesium oxide may be used, although these have been reported as giving too much burnishing action, and relief polishing.⁶

Manufacture and Properties of Tin and Tin Alloy Die Castings

By Bruce W. Gonser*

Complete statistics on the production of tin die castings are not available, but in 1937 one company produced over 180,000 lb. for a variety of uses which indicates that there is a fair volume of production.

Manufacturing Characteristics—Tin and alloys of tin used in die casting have a relatively low melting range and are not difficult to handle. They cast easily and rapidly without die injury. The heat to be absorbed is relatively small and severe temperature extremes are not encountered, even though the die may be water cooled, hence 0.20-0.50% carbon steel or cold rolled steel can be used in making dies. For information on dies for die castings see the article in this Handbook, "Composition and Heat Treatment of Dies for Die Castings".

A new die should have some lubrication during the first few days of use. Lard oil is often used, sometimes being sprayed into the die cavity by means of an air hose. Since an oxide film forms over the die with use, lubrication is soon unnecessary. There seems to be no appreciable attack or alloying of the tin with the dies.

In preparing the usual tin-base alloy, the tin is first melted then any required lead, antimony, and copper added, the temperature being kept around 800-900°F. for rapid action. As shown in Table I, the melting ranges vary widely with the composition. The influence of copper is particularly important in this respect, hence particular attention must be given in the case of the high copper alloys to assure a temperature sufficiently high to give a reasonably rapid melting and even distribution of the copper. Such an alloy must be kept well stirred to prevent segregation and, if poured into ingots for later use, cooling should be rapid. Ordinary cast iron pots have been found to be satisfactory for making the tin alloys and for the die casting pot. Fluxes are used in alloying and remelting, such as equal parts of charcoal, powdered rosin and ammonium chloride, but not in the die casting machine. The alloys are invariably made in a separate pot and usually charged to the die casting pot while molten. Finely powdered talc has been used satisfactorily as a mechanical covering over the bath in the machine. It not only prevents excessive oxidation but helps insulate the bath.

When die casting, the temperature is kept safely above the melting range, a compromise being effected between the tendency toward segregation at a comparatively low temperature and the greater dross formation, and cooling necessary at a higher temperature. From 50-100°F. above the liquidus is a fair guide. Even with a safe temperature margin, however, the metal in the casting pot must be kept well stirred to prevent segregation. Low temperature segregation may result in uneven shrinkage and even cracks in the casting.

Pressures used vary widely with the type of machine in operation, as from 200-1,500 psi. with 350 psi. as a fair average. The limit on size of tin-base die castings is usually set at 10 lb., but by far the greatest number weigh less than 1 lb.

Because of the low solidus point, shrinkage of tin-base die castings is slight and dimensional specifications may be closely held. Thus United States Army specifications permit only ± 0.0005 in. per linear in. variation for tin-base die castings compared to double this amount for lead or zinc and ± 0.0025 for aluminum-base die castings. A number of products are consequently die cast from tin alloys where close tolerances are essential. Some speedometer and odometer parts are die cast from a tin alloy with a maximum dimensional variation of ± 0.0002 in. per linear in. Cast threads up to 32 to the in. may be made. Small castings having walls only $\frac{1}{16}$ in. in thickness can be cast.

Tin-base die castings seldom require finishing but they may be easily buffed and coated. Flins and risers are readily clipped since the metal is relatively soft. Self threading screws are frequently used. These alloys machine somewhat like copper in that the tool tends to dig in. Cutting lubricants are unnecessary.

Tin-Base Die Casting Alloys—A great many tin-base alloys have been die cast in the past and, although there has been some tendency to simplify the list, at least a dozen different alloys were specified and made during 1937. Table I gives the compositions and approximate melting ranges of the most important of these alloys, including the 3 A.S.T.M. and 3 S.A.E. standard specifications that fall within

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this field. These standards apply to compositions used because of their bearing properties. It is significant that the 2 most important alloys from the standpoint of recent volume of production (No. 1 and No. 3) do not fall within these standards.

Table I
Tin Alloys Used in Die Casting

Alloy No.	Composition, %			App. Melting Range, °F	
	Tin	Lead	Antimony	Solid	Liquid
1	92	..	5 ½	430	590
2 ¹	91	..	4 ½	433	680
3	90 ½	..	8	435	480
4 ²	86	..	7 ½	460	870
5	83 ½	..	8 ½	464	792
6 ³	82	..	13	460	650
7	79	5	9	440	610
8 ⁴	65	18	15	358	565
9	61 ½	25	10 ½	397	540
10	61	30	6	368	450
11	60	35	5	355	380
12 ⁵	59 ½	26	9.5-11.5	...	...

¹A.S.T.M. B-35 T (Tentative Specification) Alloy Grade No. 1; similar to A.S.T.M. B-23 (White Metal Alloys) Grade No. 1; and to S.A.E. No. 10 standard specification. ²Similar to S.A.E. No. 11. ³A.S.T.M. B-35 T Alloy Grade No. 2. ⁴A.S.T.M. B-35 T Alloy Grade No. 3; similar to A.S.T.M. B-23, Grade No. 5. ⁵S.A.E. No. 12.

Permissible impurities according to the A.S.T.M. tentative standards are a maximum of 0.35 Pb, 0.08 Fe, 0.08 As, 0.01 Zn, and 0.01 Al with a maximum of 0.15 As in the case of Alloy Grade No. 3 (No. 8 in Table I). S.A.E. maximum impurities are 0.35 Pb, 0.08 Fe, 0.10 As, 0.08 Bi, no Al or Zn. Permissible variation from the composition of the specified standard, as proposed in the A.S.T.M. specifications, is not over 0.25% for an element present to the amount of 2% or under, 0.50% for elements between 2 and 5%, 0.75% for elements between 5 and 10% and 1% variation for elements over 10%.

Physical Properties—Tests are now in progress under the supervision of the A.S.T.M. to determine the physical properties of the A.S.T.M. standard alloys (No. 2, 6, and 8, Table I). Physical properties of the S.A.E. tin-base Babbitts (No. 2, 4, and 5, Table I) are given under the Handbook Section on Properties of Tin-Base Bearing Alloys.

As a class the tin-base die casting alloys are similar in composition and properties to babbitt metals, although they are not necessarily used as bearings. The tensile strength, hardness, and proportional limit increase, as a general rule, with increasing copper and antimony additions. The tensile strength may vary in this respect from about 10,000-18,000 psi. in the absence of lead. Addition of lead softens the alloy, lowers the melting range. Strength and hardness decrease rather rapidly with increases in temperature, particularly in the case of the alloys containing considerable lead. These alloys are all used to best advantage where strength and impact resistance are not important.

Applications—Most of these die castings are used because of their bearing properties, because of the accurate dimensions to which they can be cast, and in connection with certain types of food handling equipment. In former years most of the production was in casting bearing shells which were inserted in a proper backing; later the babbitt linings were cast directly in a strong metal backing. The wide spread use of centrifugally cast bearings and of other casting means has greatly reduced this field for die casting but many bearings are still made satisfactorily and economically in this way. Quick cooling under pressure in die casting results in a desirable fine-grained structure.

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The Zinc Industry

By R. K. Waring*

Zinc Ores—The principal ores are the sulphide, blende; the silicate, willemite; and the oxides, franklinite and zincite. The sulphide is the most widely distributed and is today the principal source of zinc. Sulphide deposits of commercial importance occur in many parts of the world. The only known large deposits of willemite and franklinite are in New Jersey.

Manufacture¹—The sulphide ore is first concentrated usually by flotation. The concentrate is roasted in the presence of air, yielding zinc oxide and sulphur dioxide which is usually converted to sulphuric acid.

Several processes are in use for producing metallic zinc from the roasted ore. The oldest is the horizontal retort process, developed in Belgium about 1806 and first used in the United States in 1859, at Bethlehem, Pa. In this process, ore mixed with coal is charged by hand into small externally fired horizontal retorts. The temperature necessary to reduce the zinc oxide to metallic zinc is above the boiling point of zinc thus producing zinc vapor. Each retort has a condenser attached to it in which the vapor condenses. The molten zinc is tapped at intervals. When the zinc has been largely reduced, the charge is removed. A complete cycle usually takes 24 hr.

In recent years a new process has been developed in which the ore and coal are briquetted and charged into large vertical retorts externally gas fired and built of refractories with good heat conductivity. The charge moves continuously down through the retort and the zinc vapor passes in a continuous stream into a condenser.

The third commercially important method of producing zinc is by the electrolytic process. In this process the roasted ore is dissolved in sulphuric acid. The resulting zinc sulphate solution is purified and the zinc plated out by electrolysis. Very careful control of the purity of the solution is essential to successful operation.

In the retort process the purity of the product depends largely on the impurities in the ore. To a limited extent, the purity of the product can be controlled by initially removing objectionable impurities from the ore. In order to produce zinc of the high purity required for some purposes, however, a refining process has recently been developed in which the impure zinc is subjected to fractional distillation in a rectifying column. A large tonnage of metal containing 99.99+ % zinc is now produced by this process. Zinc of similar purity is also produced by an electrolytic process. In this case the high purity is attained by chemical purification of the zinc sulphate electrolyte.

Grades—The recognized commercial grades of zinc in the United States have been specified by the A.S.T.M.² and are as follows:

	Lead	Iron	Cadmium	Aluminum	Sum of Lead, Iron, Cadmium
(1a) Special High Grade, max., per cent.....	0.007	0.005	0.005	None	0.010
(1) High Grade, max., per cent.....	0.07	0.02	0.07	None	0.10
(2) Intermediate, max., per cent.....	0.20	0.03	0.50	None	0.50
(3) Brass Special, max., per cent.....	0.60	0.03	0.50	None	1.0
(4) Selected, max., per cent.....	0.80	0.04	0.75	None	1.25
(5) Prime Western, max., per cent.....	1.60	0.08	...	....	...

The amount and kind of impurities in the metal have an important influence on the physical and chemical properties of zinc and its alloys.

Uses—The consumption of zinc by uses in the United States for 1936 is given in Table I³.

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Table I

Purpose	Tons
Galvanizing (total)	242,000
Sheets	132,000
Tubes	36,000
Wire	30,000
Wire Cloth	6,000
Shapes	38,000
Brass making	168,000
Rolled zinc	55,000
Die castings	72,000
Other purposes	48,000
Total	827,000

Galvanizing, which constitutes the largest use of zinc, is done either by dipping the iron in molten zinc or by electroplating. Hot dip galvanizing is done largely with the less pure grades of zinc. In some cases, such as wire, which must stand bending without flaking of the coating, High Grade or Special High Grade zinc is used. In electrogalvanizing, the zinc may be obtained either from zinc anodes or by direct solution from ore and subsequent purification of the electrolyte. High Grade and Special High Grade zinc are used to a large extent for anodes in the former method. The life of galvanized material is proportional to the thickness of the coating and recent developments in both electrogalvanizing and hot dip galvanizing have been in the direction of applying heavy coatings which will withstand deformation without peeling.

All grades of zinc are used to some extent in brass. The grade used has considerable influence on the properties of the brass. The manufacture and use of brass are discussed elsewhere in this volume.

All grades of zinc from Prime Western to Intermediate are used for rolling. In general, the presence of natural impurities or added metals increase the hardness and stiffness of rolled zinc. Special combinations of lead, iron, and cadmium are used to control the chemical characteristics of zinc for dry batteries and photo-engraving. Rolled zinc is discussed in greater detail in the article on "Wrought Zinc and Zinc Alloys".

The use of zinc-base alloys for die casting has become important in recent years and is increasing rapidly. It is essential for best results to use Special High Grade zinc for this purpose. Zinc die castings are described in a separate article in this volume.

Other forms of zinc include zinc oxide and zinc sulphide, widely used in paint and rubber, and zinc dust, used as a pigment in priming paints for metal.

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Constitution of Zinc-Aluminum Alloys

E. A. Anderson,* M. L. Fuller,† and G. Edmunds†

The phase equilibrium diagram of the zinc-aluminum system has been studied intensively. Several excellent papers have recently appeared that offer additional and more accurate data on the location of phase boundaries and one of the papers suggests a modification of the form of the existing diagram. Because of the generally admitted uncertainty of portions of the diagram, it has been considered advisable to reproduce first the diagram based on the work of Hanson and Gayler¹ and of Peirce² and then to report the results of the more recent investigations. This diagram is shown in Fig. 1. The essential form of this diagram agrees with those reported by Tanabe,³ Ishihara,⁴ and Owen and Pickup.⁵

The structure of the beta constituent and the mechanism of its decomposition have been extensively investigated. It is generally agreed that the structure of this phase is crystallographically the same as gamma, that is, a substitutional solid solution of zinc in aluminum. This has been shown by X-ray diffraction studies⁶ of Schwarz and Summa,⁷ Schmid and Wasserman,^{8,9} Owen and Iball,¹⁰ Kennedy,¹¹ Fuller and Wilcox,¹² Kossolapow and Trapeznikow,¹³ and Owen and Pickup.⁵ These papers and others¹⁴ (Meyer,¹⁵ Bugakow,¹⁶ Fraenkel and Scheuer,¹⁷ Fraenkel and Wachsmuth,¹⁸ Imal and Haglya,¹⁹ and Broniewski, Kucharski, and Winawer²⁰) also report upon various phenomena accompanying the transformation and upon the mechanism of the decomposition. Owen and Iball,¹⁰ Owen and Pickup,⁵ and Kossolapow and Trapeznikow¹³ show by X-ray methods that the beta plus gamma region of the diagram is indeed a two-phase region, the two phases having face-centered cubic structures of slightly different lattice dimensions.

Schmid and Wasserman⁸ were unable to determine the solid phase relationships in the region from 0-80% zinc at temperatures above 350°C. They suggest that the peritectic at 443°C. does not exist and that beta and gamma are one phase.

Fink and Willey²¹ have made a careful investigation of the solid alloys from 0-80% zinc at temperatures up to about 400°C. This work was performed by the electrical conductivity and microscopical methods. Fig. 2 reproduces²² the experimental results of Fink and Willey and also the results of Owen and Pickup⁵ and of Schmid and Wasserman.⁸ The several boundaries associated with the peritectic reaction, as shown in Fig. 1, are reproduced in Fig. 2 as dotted lines. The novel feature of the Fink and Willey diagram is the closed field $\beta_1 + \beta_2$, above which the beta and gamma phases are one phase.

This renders unnecessary the concept of a peritectic at 443°C.

Rosenhain and Archbutt,²³ Bauer and Vogel,²⁴ Tanabe,³ and Ishihara⁴ have presented evidence definitely indicating the existence of a peritectic reaction. The work of Owen and Pickup⁵ is in agreement with the existence of a peritectic and suggests that the beta plus gamma region above 360°C. becomes very narrow. This is in good agreement with the work of Tanabe.³ Gayler,²⁵ in discussing the paper of Fink and Willey,²¹ states that she has recently conducted experiments with zinc-aluminum alloys of the highest purity to retest the existence of a peritectic. Thermal analysis by heating and cooling curves demonstrated that a reaction of some kind takes place at 443°C. Gayler's discussion considers several hypothetical diagrams to account for the observed data and states that additional experiments are being

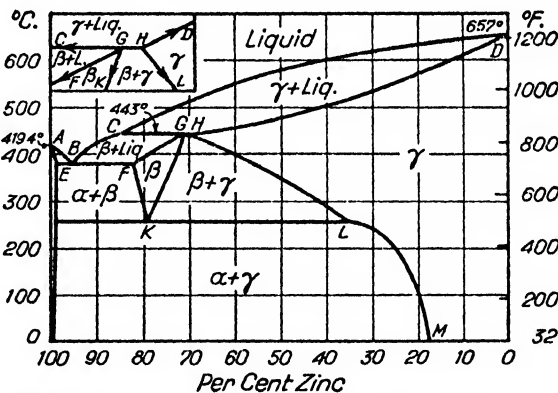


Fig. 1—Zinc-aluminum constitution diagram (Hanson and Gayler-Peirce).

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conducted to redetermine the nature of the diagram in the region of the peritectic. Unfortunately, the results of Gayler's new experiments have not been published up to the present writing. Fink and Willey²² in replying to Gayler's discussion proposed another hypothetical diagram which would be compatible with their experimental results and also with the existence of the peritectic reaction.

Although the central portion of the diagram is in an unsettled state, the terminal solid solution phases have been charted quite carefully. The combined work of Owen and Pickup,²⁰ Schmid and Wasserman,²⁰ and Fink and Willey,²² as represented in Fig. 2, yields data on the solid solubility of zinc in aluminum which are doubtlessly more accurate than the earlier data.^{1, 25, 26, 27, 28} Until the last few years the only careful study on the solid solubility of aluminum in zinc had been that of Peirce.¹ The recent papers are those of Fuller and Wilcox,²⁹ Burkhardt,³⁰ and Auer and Mann.³¹ The data from these sources are given in Table I.

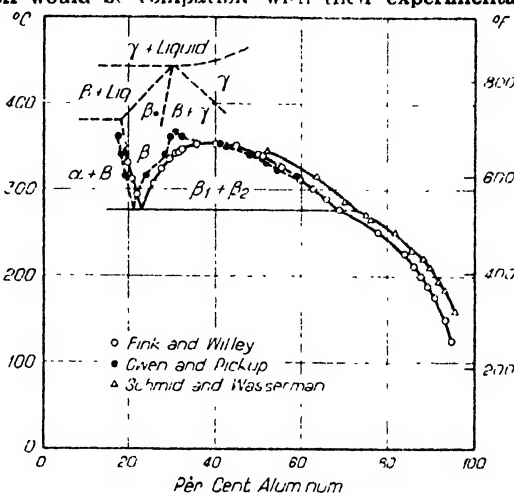


Fig 2—Beta-gamma relationship.

Table I
Solid Solubility of Aluminum in Zinc

Temperature, °C.	Peirce ¹	Fuller and Wilcox ^b	Burkhardt ^b	Auer and Mann ^c
Room		0.04%	0.05%	
95		0.08		
100			0.12	0.12%
150		0.18	0.23	0.23
175		0.28		
200		0.35	0.38	0.38
230				
250			0.45	0.57
300			0.6	0.78
335	0.85			
370				1.08
375		0.78		
380			0.8	

^aElectrical conductivity method ^bX-ray diffraction method. ^cMagnetic susceptibility method

The eutectic temperature of 380°C. and the eutectic composition of 5% aluminum remain unchanged from the original work of Rosenhain and Archbutt.³⁴

The eutectoid composition is placed at about 21% aluminum by the work of Hanson and Gayler¹ and that of Tanabe.³ The work of Fink and Willey²² indicates a composition of 22% aluminum for this point. It is interesting to note that the hypothetical compound Al₂Zn₃ has an aluminum content of 21.6%.

The eutectoid temperature has been determined by many investigators. The original determination of Rosenhain and Archbutt³⁴ of 256°C. has been shown to be too low for the reason that too rapid rates of cooling were used in determining the cooling curve through the eutectoid transformation. This was demonstrated in the paper by Fuller and Wilcox²⁹ who worked with heating and cooling curves of various rates and determined that 277°C. was a more probable value for the eutectoid temperature. Fink and Willey²² by electrical conductivity analysis place the temperature at 275°C. The X-ray measurements of Owen and Pickup²⁰ indicate a eutectoid temperature of 272°C. Tanabe³ reported 270°C., and Ishihara⁴ and Jares²³ each reported 280°C.

The crystal structure of the alpha phase is hexagonal close-packed. The lattice dimensions differ from those of pure zinc by reason of the substitution of aluminum

for zinc, the lattice being expanded in a direction parallel to the trigonal axis and contracted in directions perpendicular to this axis.^{11, 12, 13, 14} The gamma phase has the face-centered cubic structure of aluminum, the substituting zinc atoms causing a general lattice contraction. This contraction amounts to 0.00083A per unit cell length per atomic per cent zinc according to Schmid and Wasserman.¹⁰ The beta phase is crystallographically the same as gamma and for a composition of 20.0% aluminum has a unit cell size of 3.991A at room temperature.¹³

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The Constitution of Zinc-Cadmium Alloys

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The zinc-cadmium system is of the simple eutectic type showing solid solubility on both the zinc and cadmium sides.

The liquidus has been determined by numerous investigators, most of the values falling well within 10° variation. The agreement on the eutectic concentration (17.4% Zn) is good, but the temperature values vary between about 260 and 270°C.; 265°C. is probably a fair average.

There is need of a thorough and careful study of the solid solubilities on both sides of the diagram. The divergence of values is shown in Table I for some recent determinations at or near the eutectic temperature.

Table I
Solid Solubilities of Cadmium in Zinc

	Zinc, %	Cadmium, %	Method
Peirce .....	.....	1.0-2.0 (250°C.)	Electrical conductivity and microscopic
Jenkins	2.0-2.25 (250°C.)	1.75-2.0 (250°C.)	Microscopic
Grube and Burkhardt.....	4.3	3.7	Electrical resistivity
Stockdale	2.95	2.15	Microscopic
Boas .....	.....	1.8 (250°C.)	X-ray
LeBlanc and Schöpel.....	3.0-4.2	3.4-5.0	Electrical resistivity and microscopic

Since values as low as 0.1% have been reported at 100°C. and room temperature, it is apparent that the solid solubility in zinc drops sharply with temperature. This coupled with insufficient annealing or inadequate quenching may account for the divergence.

With rising temperature above the eutectic, Jenkins and Stockdale agree in showing on the zinc side an increase in solid solubility followed by the normal decrease (a solidus curve reversing with temperature). Their explanation based on an alleged allotropy of zinc is not tenable, however, in view of the abundant evidence against the existence of such allotropes.

Fig. 1 shows our present knowledge of the system.

Recent studies of the eutectic by Zagorodskikh* and by Straumanis and Brakss* show the two phases to have a definite orientation relationship with a strong probability that the basal planes of zinc and cadmium are parallel and that the close packed directions coincide.

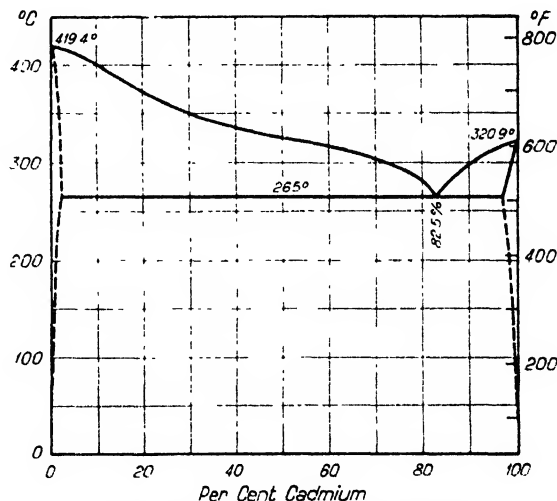


Fig. 1—Zinc-cadmium constitution diagram

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The Zinc-Rich Portion of the Zinc-Copper Constitution Diagram

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The zinc-rich portion of the zinc-copper diagram is shown in Fig. 1. Three recent investigations of the solid solubility of copper in zinc are in substantial agreement. The data of Anderson, Fuller, Wilcox, and Rodda¹⁷ either fall between the values of Hansen and Stenzel¹⁵ and of Burkhardt¹⁸ or close to one or the other.

The peritectic temperature (ϵ + liquid = η) has been determined by numerous investigators,^{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11} all but a few placing it between 423 and 425°C. The agreement in the location of the peritectic point (solid solubility at the peritectic temperature) is not so good. The best agreement is between the work of Shepherd² (2.5%), Hansen and Stenzel¹⁵ (2.66%), and Anderson, Fuller, Wilcox, and Rodda¹⁷ (2.68%).

Determinations below the peritectic point of the liquidus^{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11} are not numerous. The range between the two curves is but a few degrees at the most. The data of Anderson, Fuller, Wilcox, and Rodda¹⁷ have been accepted here.

Various authorities^{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11} largely on the basis of cooling curve data, have placed the intersection of the peritectic horizontal with the liquidus between 1.5% and 2.0% copper. According to Peirce³ primary epsilon was found in chill cast specimens containing 1.81% copper but not in those with 1.5% copper. The value 1.7% copper as plotted in

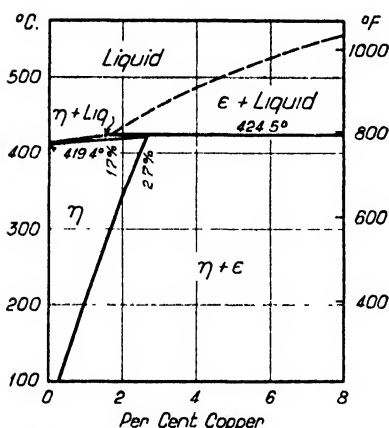


Fig. 1—The zinc-rich portion of the zinc-copper constitution diagram.

Fig. 1 is the most probable. The course of the liquidus above the peritectic temperature must be considered uncertain by several degrees, since it was determined by cooling curves which are subject to error by undercooling of the melt.

The crystal structure of the eta solid solution and the epsilon phase have both been determined as hexagonal close packed^{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11} with lattice constants as follows:

Phase	A ₀	C ₀	c/a
Pure zinc.....	2.660A	4.938A	1.856
Eta solid solution (1% Cu).....	2.665A	4.896A	1.837
Epsilon (saturated with zinc at 200°C.)....	2.753A	4.290A	1.559

The Widmanstätten structures formed by the segregation of epsilon from eta have been analyzed.¹⁶ The plane of segregation is a {10.4} plane with a strong probability that the conjugate plane of the segregate is also a {10.4} plane.

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Constitution of Zinc-Iron Alloys

By E. A. Anderson,* J. L. Rodda,† and G. Edmunds†

The phase boundaries shown in Fig. 1 and 2 are derived principally from the work of Schramm^{2,3,4} and of Truesdale, Wilcox and Rodda⁵ but represent also a careful consideration of older data.

There are five†† well established phases in this system (Fig. 1). A new phase containing 6% iron and formed by a peritectic reaction at 530°C. has recently been proposed (Fig. 2). These phases are tabulated in Table I. To avoid confusion the nomenclature of Schramm and the older designations are both given.

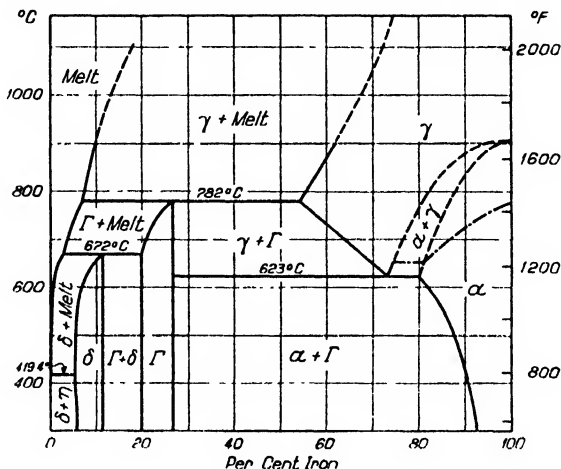


Fig. 1 Zinc-iron constitution diagram

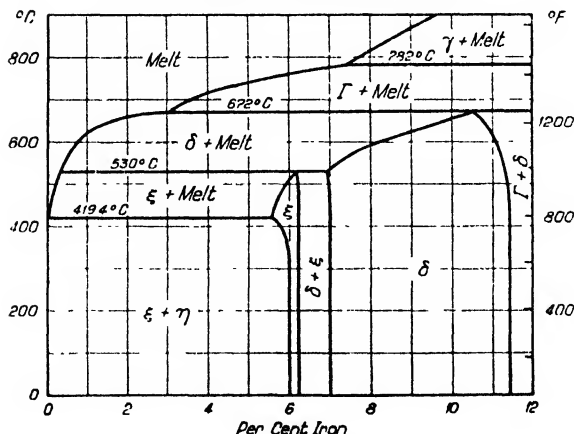


Fig. 2—Zeta phase of the Zinc-iron constitution diagram

Truesdale, Wilcox and Rodda investigated the zinc end of the diagram up to 875°C. The liquidus was determined by direct sampling of the supernatant liquid.

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^{2,3,4}This apparently valuable work covered the determination of several of the phase boundaries on which little or no work had previously been reported. It has also included the first report of the zeta phase. It would be desirable for these determinations to be checked.

††The high temperature body-centered cubic form of iron, delta, is not considered here since its stable region is above the temperatures usually investigated.

Peritectic horizontals were fixed at 672 and 782°C. by heating curves. The solid solubility of iron in zinc was found by microscopic methods to lie between 0.0009 and 0.0028% at temperatures from 150-400°C. A eutectic was noted at about 0.018% iron with a eutectic lowering of less than 0.05°C.

Above a few per cent iron, the preparation of homogeneous and nonporous zinc-iron alloys is difficult. By a unique method of preparing alloys between 4 and 20% iron, Schramm prevented the usual expansion and excessive porosity and produced alloys suitable for microscopic examination. Alloys containing from 20-100% iron were prepared by annealing highly compressed powder mixtures of iron with a zinc-iron alloy containing 15% iron. The need of extremely high temperatures and consequent high pressures to prevent volatilization of zinc was thus avoided. Dense alloys appear to have been produced. Thermal arrests, micrographic, X-ray and magnetic methods were used to investigate the diagram.

The solidus boundaries of the phases Γ ($\text{Fe}_3\text{Zn}_{10}$) and δ (FeZn_7) were determined for the first time by Schramm. The boundaries γ ($\gamma + \Gamma$), γ ($\gamma + \text{liquid}$) and α ($\alpha + \Gamma$) were determined by microscopic analysis, the last boundary being checked by X-ray studies.

Table I
Phases of the Zinc-Iron System

Schramm	Phase Older Designation	Approximate Limits of Composition, % Iron	Crystal Structure	Description
η (eta)	Zinc	0-0.0028	Close packed hexagonal	Zinc with minute amount of iron in solid solution
ζ (zeta)	New	6 ± 0.25	Pattern similar to delta	Formed by peritectic reaction at 530°C.
δ (delta)	FeZn_7	7-11	Hexagonal	Formed by peritectic reaction at 672°C.
Γ (Gamma)	$\text{Fe}_3\text{Zn}_{10}$	20-27	Cubic, 52 atoms to unit cell	Formed by peritectic reaction at 782°C.
γ (gamma)	γ	55-100	Face-centered cubic	Solid solution of zinc in iron
α (alpha)	α	80-100	Body-centered cubic	Solid solution of zinc in iron

The boundaries of an ($\alpha + \gamma$) field have been drawn from meager data. This region needs further study, especially in view of the evidence of Jones²⁴ and of Svechnikov and Gridnev that the temperature of the ($\alpha - \gamma$) transformation is raised by the addition of zinc. The latter claim that no gamma is present in alloys over 17% zinc.

The peritectic temperatures of Schramm, 780 and 668°C. agree with the values of Truesdale, Wilcox and Rodda. A eutectoidal decomposition of γ into ($\alpha + \Gamma$) at 623°C. was demonstrated as indicated by earlier workers. This agrees with the temperature found by Ogawa and Murakami¹² but is about 20°C. lower than the value of Raydt and Tammann.⁶

The temperature of the magnetic transformation was determined by Raydt and Tammann,⁶ Ogawa and Murakami,¹² Fallot,²⁵ and by Schramm.²² It is to be noted that this is not the temperature of the ($\alpha - \gamma$) transformation except in the region between the eutectoid (γ) composition and Γ ($\text{Fe}_3\text{Zn}_{10}$). All agree that the addition of zinc in solid solution lowers the temperature of the magnetic transformation in iron.

The new zeta phase described by Schramm (Fig. 2) has a narrow compositional range near 6% iron and is formed by peritectic reaction at 530°C. between δ (FeZn_7) and melt. The reaction involves a much larger proportion of solid than liquid, is sluggish and may often be almost completely suppressed. The X-ray work has not been reported in detail but the pattern is said to be similar to delta. The formation of this phase may be associated with the high rate of attack of iron by molten zinc observed by Grubitsch²⁷ and others²¹ in the neighborhood of 500°C.

The crystal structures of the phases have been investigated by a number of workers.^{12, 22, 23, 24, 25, 26, 27} The generally accepted structures are given in Table I.

In conclusion it may be stated that the phases present in the system appear to be well established, except that the newly described zeta phase should be confirmed. The nature of the ($\alpha - \gamma$) transformation and the related eutectoidal decomposition need further investigation. The suggestion of Bablík,²⁴ discussed by Jones²⁴ that the appearance or disappearance of some phases may be a function of the pressure during formation, deserves consideration. It is, moreover, obvious

that the extension of the liquidus above about 900°C. is possible only at pressures greater than atmospheric, since otherwise zinc would vaporize. When dealing with alloys above this temperature, it must be kept in mind that the diagram as given represents higher than normal pressures.

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Constitution of Zinc-Lead Alloys

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The equilibrium relations in the zinc-lead system have recently been investigated in detail and the diagram obtained is given in Fig. 1. The system is a simple eutectic type. The relations in the liquid state are complicated by the presence of two liquid phases over a large range of concentration at temperatures ranging from the melting points of the pure metals to those approaching the boiling point of zinc.

Earlier investigations of this system were carried out by Matthiessen and von Bose,¹ Spring and Romanoff,² Wright and Thompson,³ Arnemann,⁴ Heycock and Neville,⁵ Guertler,⁶ Kremann and Knabl,⁷ and Peirce.⁸

Hodge and Heyer,⁹ in a recent investigation of the lead-rich regions, place the eutectic concentration at 99.5% lead and the eutectic temperature at 318°C. Their evidence, based on slowly cooled, but not annealed specimens indicates that the solid solubility of zinc in lead at the eutectic temperature is 0.05%. A microscopic study of zinc-rich alloys in this laboratory¹⁰ indicates that the solid solubility of lead in zinc is definitely less than 0.0019% and possibly below 0.0002%. That a definite, though slight, solubility does exist is evidenced by a growth of the lead particles on annealing.

Hass and Jellinek¹¹ determined the mutual liquid solubility of zinc and lead between 400 and 750°C. by a method in which samples of the liquid were obtained at desired temperatures. The results obtained are in agreement with the results obtained by Waring, Anderson, Springer, and Wilcox¹² at temperatures near the melting point but disagree at higher temperatures.

Waring and associates¹² investigated the zinc-lead system in detail with special reference to liquid solubility. The temperature horizontals for the zinc monotectic and the lead eutectic were placed at 417.8 and 318.2°C., respectively. The liquid solubility curve was established by four different methods and the solubility was found to be higher and the temperature of complete miscibility (790°C.) lower than that reported by any previous investigator. On the basis of rather scanty vapor pressure data, Jellinek and Wannow¹³ have recently questioned these results. The chances of error in the vapor pressure data and in the diagram constructed from these data are considered greater than in the four direct methods of Waring and associates. Waring and Springer¹² have extrapolated the latter data, plotted as $\frac{1}{T}$ against log of the mol fraction of lead in the liquid phase,¹⁴ to the monotectic temperature, fixing the concentration of the monotectic at 0.9% lead. The new method of plotting the data alters slightly the interpolated values originally published. The new values are given below for selected temperatures.

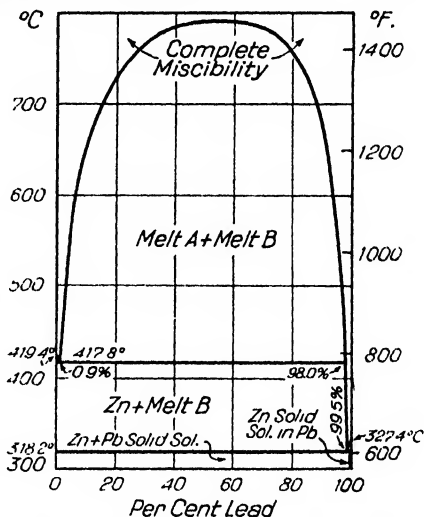


Fig 1—Zinc-lead constitution diagram

Temperature, °C.	% Pb in Zn	% Zn in Pb	Temperature, °C.	% Pb in Zn	% Zn in Pb
417.8	0.9	2.0	650	9	8
450	1.3	2.3	700	15	12
500	2.2	3	750	24	19
550	3.8	4	775	32	26
600	5.6	6	790	Complete miscibility	

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Constitution of Zinc-Magnesium Alloys

E. A. Anderson* and J. L. Rodda†

The diagram in Fig. 1 of the zinc-magnesium system represents a combination of the data of Hume-Rothery and Rounsefell,¹⁰ Chadwick,¹¹ and Schmid and Seliger.¹²

An intermetallic compound, $MgZn$, (melting point $590^{\circ}C$.) is formed by primary separation from the molten alloys containing 3-46% magnesium. Two additional compounds, $MgZn$ and $MgZn_2$ (Mg_2Zn_3 , according to Laves and St. Werner¹³), are formed through peritectic reactions of $MgZn$, with the melt at $354^{\circ}C$ and $380.5^{\circ}C$, respectively. Solid solution in the compounds $MgZn$ and $MgZn_2$, as claimed by Chadwick¹¹ has been denied by Hume-Rothery and Rounsefell.¹⁰ Botschwar and Welitschko¹⁴ confirm Chadwick's claim.

A new temperature horizontal at about $265^{\circ}C$. was found by Grube and Burkhardt,¹⁵ using electrical resistance measurements. G. Edmunds¹⁶ concludes, after a careful examination of these data, that the diagram between 20-100% magnesium is more complicated than has heretofore been indicated and that a eutectoid inversion probably occurs in most of these alloys at about $265^{\circ}C$. Microstructural examinations of alloys in this region have confirmed this discovery, but no extensive investigation has been made which would definitely establish this portion of the diagram.

Schmid and Seliger,¹² using X-ray measurements of lattice constants, have determined the following values for the solid solubility of zinc in magnesium.

Temperature, $^{\circ}C$	340*	300	250	200	150
% Zinc	8.4	6.0	3.3	2.0	1.7

*Eutectic temperature.

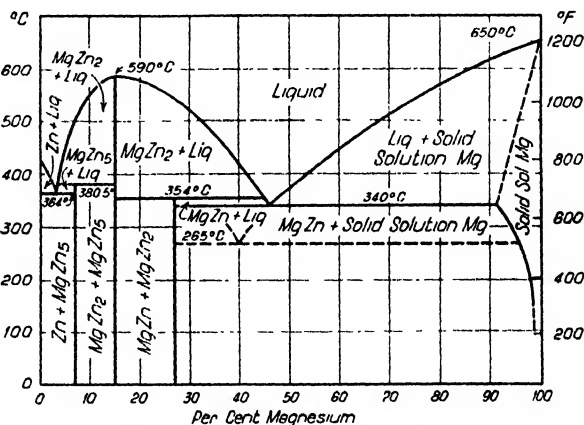


Fig. 1—Zinc-magnesium constitution diagram.

Hansen,¹⁰ in his review of the system, considers these determinations to be the most reliable.

Evidence of a limited solid solubility (approximately 0.1% at $360^{\circ}C$.) of magnesium in zinc has been found by Chadwick¹¹ and Hume-Rothery and Rounsefell.¹⁰ Unpublished data from the authors' laboratory indicate that this falls off to less than 0.002% at room temperature.

Friauf¹⁷ and Tarschisch¹⁸ have investigated the crystal structure of the compound $MgZn$, and found it to be hexagonal. Friauf's parameter values are as follows: $a = 5.15A$, $c = 8.48A$, $c/a = 1.64$.

The compounds $MgZn$ and $MgZn_2$ are both considered by Tarschisch¹⁸ to be hexagonal, McKeehan¹⁹ concludes, after an analysis of Tarschisch's work that these structures require more experimental verification before they can be regarded as established.

Edmunds and Fuller²⁰ have determined the structure of $MgZn$, as a body-centered cube, with 52 atoms in the unit cell, in which $a = 9.44A$. Laves and St. Werner consider the compound to be Mg_2Zn_3 , with a simple cubic lattice containing 38 or 39 atoms and a cell dimension of $a = 8.29A$.

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The Zinc-Rich Portion of the Zinc-Manganese Constitution Diagram

E. A. Anderson* and J. L. Roddat†

The zinc-manganese system has been studied up to about 40% manganese. The data are in such marked disagreement, however, that this summary will be limited to alloys of not over 2% manganese. Those interested in higher manganese contents are referred to the comprehensive review of Hansen.³

The zinc end of the diagram shows a limited solid solubility of manganese in zinc and a slight depression of the melting point to form a eutectic. The solid solubility at the eutectic temperature has been variously placed between 0.5 and 1% manganese^{1, 2, 3, 4} and the eutectic concentration between 0.6 and 2.0% manganese.^{1, 2, 3, 4} The respective values of 0.5 and 1% manganese seem most probable. The solid solubility has been shown to decrease with temperature to a value near 0.1% at room temperature.²

The diagram shown in Fig. 1 is taken from Peirce's investigation.²

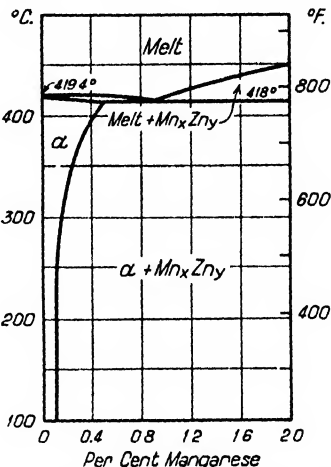


Fig. 1—The Zinc-rich portion of the zinc-manganese constitution diagram.

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The High Zinc Portion of the Zinc-Nickel Constitution Diagram

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Most of the experimental work done on the zinc-nickel system has dealt primarily with the determination of the limits of the several intermediate phases. Only a few investigators have concerned themselves with the zinc-rich solid solution.

The early work on the nickel-zinc system was thoroughly reviewed by Tafel¹ in 1908. Chiefly on the basis of thermal analysis, with some microscopical data, he concluded that a eutectic horizontal exists at 418.5°C., the eutectic concentration being about 0.25% nickel.

Two investigations of the solid solubility boundary for the zinc-rich end of the system have been carried out. In the second of these investigations, the location of the eutectic horizontal at 418.5°C. was confirmed.

In 1922, Peirce² concluded that the eutectic point must lie between 0.12 and 0.25% nickel. He noted at the time a structural association of the nickel-zinc eutectic with the lead-zinc monotectic which may have some bearing on this portion of the zinc-nickel system. From microscopical studies and electrical resistivity measurements, Peirce concluded that the solid solubility at room temperature is less than 0.034% nickel and that the solubility increases with increasing temperature to a value of not over 0.1% nickel.

In 1933, Heike, Schramm, and Vaupel³ conducted an investigation on vacuum-melted alloys very carefully homogenized and brought to equilibrium. On a basis of microscopical examination, these workers placed the eutectic at 0.25% nickel. They found the solid solubility of nickel in zinc to be 0.05%, independent of the temperature. The X-ray methods employed by Caglioti⁴ were unable to detect any solubility of nickel in the zinc lattice.

Fig. 1 and 2 show the zinc-rich portion of the zinc-nickel system according to Peirce and according to Heike, Schramm, and Vaupel.

While the main essentials of this portion of the diagram seem to be clearly defined, there seems to be necessity for further work, preferably with purer materials, if the exact locations of the eutectic and of the solid solubility boundary are to be determined.

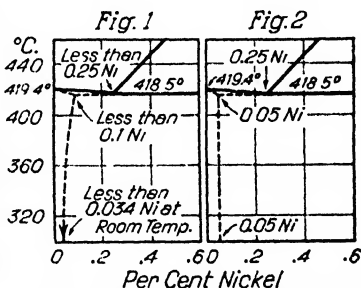


Fig. 1—Solid solubility of nickel in zinc according to Peirce.

Fig. 2—Solid solubility of nickel in zinc according to Heike, Schramm and Vaupel.

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The Constitution of the Silver-Zinc Alloys

By E. A. Anderson* and J. L. Rodda†

The diagram shown in Fig. 1 is essentially that given in Hansen's comprehensive review,¹⁰ but has been modified slightly to fit more recent data. Hansen's diagram is based on the following principal sources of data:

Heycock and Neville¹: Liquidus

G. J. Petrenko², Ueno³: Liquidus, solidus, temperatures of peritectic reactions ($\alpha + \text{melt} \rightleftharpoons \beta$, $\gamma + \text{melt} \rightleftharpoons \epsilon$, $\epsilon + \text{melt} \rightleftharpoons \eta$), β transformation.

Carpenter and Whiteley⁴: Solubility boundaries, temperatures of peritectic reactions ($\alpha + \text{melt} \rightleftharpoons \beta$, $\gamma + \text{melt} \rightleftharpoons \epsilon$, $\epsilon + \text{melt} \rightleftharpoons \eta$).

G. J. Petrenko and B. G. Petrenko⁵: Temperature and extent of the peritectic reaction, $\beta + \text{melt} \rightleftharpoons \gamma$. A somewhat questionable transformation at 228°C. in the ($\zeta + \gamma$) field.

More recently Hume-Rothery, Mabbott and Evans¹⁴ have determined the alpha solidus by quenching experiments and these data have been used in Fig. 1. The X-ray determinations of phase boundaries by Owen and Edmunds¹⁵ have been indicated in the figure but it is to be doubted whether they attained equilibrium, in view of the short annealing times employed.

The resemblance of the silver-zinc system to that of copper-zinc has been frequently noted. X-ray structural studies of the beta silver-zinc alloys have been an aid in interpreting the beta copper-zinc structures. The transformation in beta silver-zinc alloys has recently been clarified by Straumanis and Weerts¹¹ and by Weerts.¹² Above the transformation temperature, the phase is body-centered cubic with a random distribution of silver and zinc atoms. Quenched specimens β' show the same structure with an ordered arrangement of atoms. This β' phase is, however, in a metastable condition. The stable phase is zeta (ζ) which Westgren¹ has found to be hexagonal. Zeta is formed by slow cooling through the transformation temperature or by the annealing or drastic cold working of β' below this temperature.¹¹

Several investigators have claimed a high solid solubility of silver in zinc. Owen and Edmunds¹⁵ value at 408°C. is 9.0% silver. From a study of microscopic specimens, Wilcox and Rodda¹⁷ believe the solubility to be less than 5% silver at 400°C. and approximately 3% silver at 300°C.

Smith¹³ has investigated the mechanism of the segregation of alpha from beta along the sloping ($\alpha + \beta$) - β boundary. Weerts¹² investigated the similar separation of gamma from beta and the transformation of beta into zeta. In all cases, the new phase was found to bear an orientation relationship to the parent crystal.

Westgren and Phragmén⁴ as well as others^{1, 18, 19} have investigated the crystal structures of the various phases. The phase structures are tabulated below:

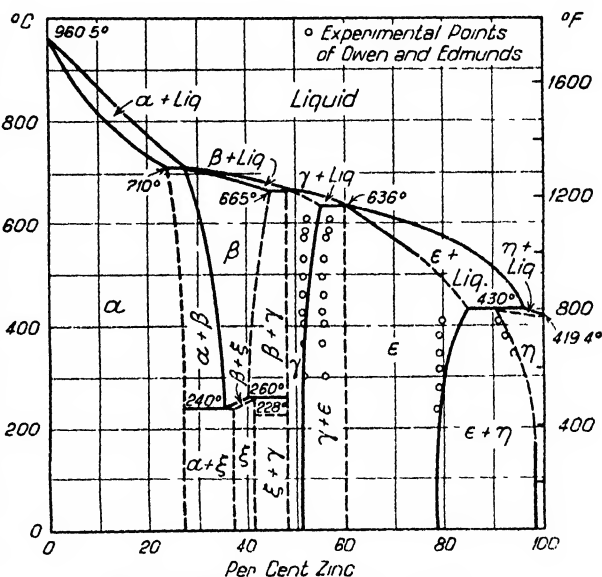


Fig. 1—Silver-zinc constitution diagram

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Phase	Structure	Atoms Per Unit Cell
α	Face-centered cubic	4
β	Body-centered cubic	2
ζ	Hexagonal	9
γ	Cubic	52
ϵ	Close-packed hexagonal	2
η	Close-packed hexagonal	2

The approximate axial ratios of the epsilon and eta phases are 1.56 and 1.8, respectively, varying slightly with composition. According to Weerts,¹¹ 0.367 is the axial ratio of the zeta phase.

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Constitution of Zinc-Tin Alloys

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The zinc-tin system is of the eutectic type with no evidence of solid solubility on the zinc side and nonconcordant indications of some solubility on the tin side.

The present diagram is substantially as found by earlier workers.^{1, 2, 3, 4, 5} The liquidus values determined by cooling curves are in substantial agreement. Before final acceptance, however, they should be checked by an alternative method. The eutectic temperature and concentration lie between 198-199°C. and 7.5-9.5% tin, respectively. After an inspection of the data, Hansen¹⁴ chose the values 199°C. and 9% tin as the most probable.

Saldau¹¹ placed the solid solubility of zinc in tin between 0.5 and 1.5% at 185°C. These results are to be questioned in view of his observation of two polymorphic changes in the zinc used in the investigation. This is quite contrary to the findings of present day metallurgists and would indicate that the zinc used by Saldau was of an impure grade. More recently Blondel and Laffitte¹² have claimed a solid solubility of 2.5% zinc.

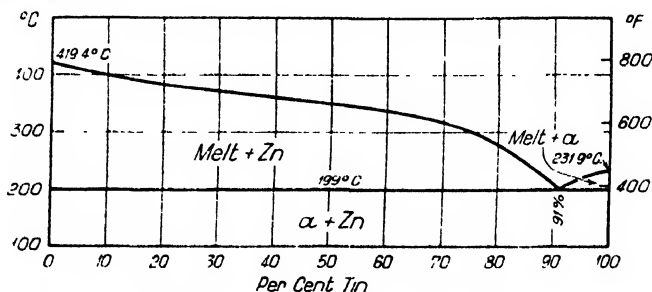


Fig. 1—Zinc-tin constitution diagram.

Peirce⁷ placed the solid solubility of tin in zinc below 0.05%. Tammann and Rocha¹³ claim the limit to lie between 0.05 and 0.1% tin. Definite effects of tin on the hot shortness of zinc have been observed in this laboratory at substantially less than 0.05% tin. If any solid solubility exists it must be less than 0.05% tin.

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Physical Constants of Zinc

By E. A. Anderson* and J. H. Craig†

Introduction—Zinc of 99.99+ % purity has been produced commercially for several years. The principal impurities are lead, cadmium, and iron. "Spectrographically pure" zinc has been produced in laboratory quantities by the vacuum distillation of high grade zinc and has been used for the determination of some physical constants.

Atomic Weight—Zinc has the atomic number 30. According to the 1939 International Table of Atomic Weights, the atomic weight of zinc is 65.38. F. W. Aston¹ reports that the isotopes of zinc are as follows, listed in the order of decreasing abundance: 64, 66, 68, 67, 65, 70, and 69. The existence of isotopes 65 and 69 is doubted, however, by K. T. Bainbridge.²

Crystal Structure—Zinc has the hexagonal close-packed atomic arrangement and has the symmetry of space group D_{6h} .³ The unit cell dimensions of the crystal lattice are $a_0 = 2.6600 \pm 0.0002\text{Å}$, $c_0 = 4.9379 \pm 0.0005\text{Å}$ and $c/a = 1.8563$ at 27°C. according to M. L. Fuller who worked with filings of 99.99+ % pure zinc. Jette and Foote, working with spectrographically pure zinc, report $a_0 = 2.6597\text{Å}$, $c_0 = 4.9367\text{Å}$ and $c/a = 1.8561$ at 25°C.

If the atomic domain of the zinc atom is considered as a prolate spheroid, it would have an equatorial radius of 1.3300Å and an axial radius of 1.5117Å at 27°C. The density calculated from the crystal structure data is 7.126 g. per cc. at 27°C.

Zinc exhibits no allotropy. Four papers which have appeared in the last decade have shown that only one crystal form exists from room temperature to the melting point. Peirce, Anderson and Van Dyck,⁴ Freeman, Sillers and Brandt,⁵ and Simon and Vohsen⁶ used the X-ray diffraction method and Anastasiadis and Guertler⁷ used the method of thermal analysis.

Specific Gravity—Chemical composition and physical state affect the specific gravity of zinc. Typical data from various investigators follow:

Type and Purity of Zinc	Temperature, °C.	D (g./cc.)
Molten, 99.94% pure.....	419.4	6.92 (3)
Cast, 99.993% pure.....	25	7.131 (6)
Rolled, 99.993% pure.....	25	7.142 (3)
Swaged, S.F. wire, 0.07 in. dia.....	25	7.133 (10)

The best values for general use seem to be 7.13 for cast zinc and 7.14 for rolled zinc.

Compressibility of Single Crystals—The determination of compressibility of zinc single crystals by P. W. Bridgman⁸ yielded the following values at 30°C.:

$$\begin{aligned}
 90^\circ \text{ Orientation} &= -\frac{\Delta l}{l_0} = 1.57 \times 10^{-11} p - 0.75 \times 10^{-13} p^2 \\
 0^\circ \text{ Orientation} &= -\frac{\Delta l}{l_0} = 13.50 \times 10^{-11} p - 7.68 \times 10^{-13} p^2 \\
 \text{Volume Compression} &= -\frac{\Delta V}{V_0} = 16.64 \times 10^{-11} p - 9.62 \times 10^{-13} p^2
 \end{aligned}$$

where p is in kg. per sq. cm.

Coefficient of Thermal Expansion—The thermal expansions of single crystals of zinc of high purity have been reported by several investigators. The determinations were made at various angles to the principal axis as shown in the following tabulation:

Grade of Zinc	Form	Orientation	Temperature, °C.	Coefficient $\times 10^4$
Spectrographically pure	Rod, 2.5 mm. in dia.	44° to the principal axis	0-50	4.00 (12)
			0-100	4.04
			0-150	4.23
			0-200	4.40
			0-250	4.58
			0-300	4.60

(Continued)

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Kahlbaum's Best (0.014% Pb, 0.012% Cd)	Rod, 2.5 mm. in dia.	Parallel to the principal axis	0-50	5.48	(12)
			0-100	5.70	
			0-150	5.74	
			0-200	5.80	
			0-250	5.81	
			0-300	5.73	
Kahlbaum's Best	Rod, 2.5 mm. to 2.2 cm. in dia.	Parallel to hexagonal axis	18	5.74	(13)
		Perpendicular to hexagonal axis	18	1.26	

On polycrystalline cast rods, 30 cm. x 0.714 cm., of 99.993% pure zinc, the Bureau of Standards¹⁰ gives the following values:

Temperature, °C.	Coefficient
20-100	3.95×10^{-5}
20-150	3.96×10^{-5}
20-200	3.97×10^{-5}
20-250	3.97×10^{-5}

The International Critical Tables give the following data on the thermal expansion of zinc:

Temperature, °C.	Coefficient
-170-60	29.5×10^{-6}
0-300	35.4×10^{-6}

Other values found in the literature, as summarized by Burkhardt,¹⁴ range from 17.1×10^{-6} to 36.4×10^{-6} . The wide variation of these results was probably caused, in part, by differences in orientation.

The following data on hot rolled zinc (99.94% pure) were obtained¹ in the range of 20-40°C.:

Direction of Test	Linear Coefficient of Expansion
With Grain	0.0000325 per °C. (0.000018 per °F.)
Across Grain	0.000023 per °C. (0.000013 per °F.)

The coefficient of cubical expansion is given in the Smithsonian Physical Tables as 89.25×10^{-6} per °C. between 0° and 100°C.

For other values on thermal expansion, see the work of Owen and Iball,¹⁵ Owen and Yates,¹⁶ Grüneisen and Goens,¹⁷ and McLennan and Monkman.¹⁸

Melting Point—The melting point of 99.94% pure zinc has been determined¹ as 419.4°C., while Roeser and Wensel¹⁹ give a temperature of 419.48°C. for metal 99.993% pure. On spectrographically pure zinc, a melting point of 419.45°C. has been obtained by the authors and 419.47°C. at the Bureau of Standards.¹⁰

Specific Heat—Determinations of specific heat by various investigators are shown in the following table:

Wüst ²⁰		Eastman, Williams and Young ²¹		Awbery and Griffiths ²²		Umino ²³	
Temp., °C.	Specific Heat	Temp., °C.	Specific Heat	Temp., °C.	Specific Heat	Temp., °C.	Specific Heat
0	0.0875	100	0.095	100-200	0.099	50	0.0940
						100	0.0946
100	0.0965	200	0.100	200-300	0.105	200	0.0981
						300	0.0981
200	0.1052	300	0.104	300-400	0.118	400	0.1002
						500	0.1022
300	0.1139	400	0.109	420-500	0.092	600	0.1473
						700	0.1444
400	0.1226					800	0.1423

Umino gave the purity of his zinc as 99.948%. No mention of purity was made by the other investigators.

For other data on specific heat at various temperatures, see Behrens and Drucker,²⁶ Keesom and van den Ende and Clusius and Harteck.²⁷

Latent Heats of Fusion, Vaporization, Sublimation—In a critical review of the literature, C. G. Maier²⁷ gives the following equations for the latent heats of fusion, vaporization, and sublimation:

Heat of Fusion

$$\Delta H_f = 685 + 1.80T - 0.745 \times 10^{-3}T^2$$

Heat of Vaporization

$$\Delta H_v = 31087 - 2.09T - 0.575 \times 10^{-3}T^2$$

Heat of Sublimation

$$\Delta H_s = 31772 - 0.29T - 1.32 \times 10^{-3}T^2$$

where ΔH_f = cal. per g. atom and T = absolute temperature.

The values derived from the foregoing equations are the most reliable obtainable. The latent heat of fusion thus obtained is 24.09 cal. per g. at 419.45°C. The latent heat of vaporization is 425.6 cal. per g. at 905.4°C.

Boiling Point and Vapor Pressure—The following values for the boiling point of zinc have been reported: C. G. Maier²⁸ 905 ± 2°C. and Bauer and Brunner²⁹ 907°C.

C. G. Maier²⁸ of the United States Bureau of Mines has given the following formula for the vapor pressure of zinc:

$$\log P = 12.0013 - \frac{6670}{T} - 1.1265 \log T$$

where P = pressure in mm. of mercury and T = absolute temperature.

Thermal Conductivity—Bidwell and Lewis,³⁰ working with a single crystal of 99.993% pure zinc, report the following values:

Temperature, °C.	Thermal Conductivity Cal. Per Sec. Per Sq. cm. Per cm. Per °C.
-200	0.36
-150	0.34
-100	0.33
-50	0.32
0	0.30
50	0.29
100	0.28

The orientation of the single crystal with respect to the direction of measurement was not stated.

Goens and Grüneisen³¹ determined the thermal conductivity of a single crystal of zinc (purity not mentioned) both parallel to and perpendicular to the hexagonal axis. Their results follow:

Temperature, °C.	Thermal Conductivity	
	Parallel to Hexagonal Axis	Perpendicular to Hexagonal Axis
-252	1.69	1.35
-190	0.316	0.328
20	0.296	0.296

Bidwell and Lewis³⁰ and Bailey³² worked with polycrystalline zinc. The first mentioned investigators used rods of 99.993% pure zinc, cast in vacuo and also in air. Bailey used rods, 0.585 cm in dia., 7-8 cm. long, turned from larger rods, of pure redistilled zinc. Their results follow:

Bidwell and Lewis			Bailey	
Temperature, °C.	Thermal Conductivity		Temperature, °C.	Thermal Conductivity
	Cast in Vacuo	Cast in Air		
-200	0.33	0.31	136	0.265
-150	0.31	0.29	153	0.257
-100	0.29	0.28	176	0.257
-50	0.28	0.27	206	0.249
0	0.27	0.26	279	0.244
50	0.26	0.25	282	0.241
100	0.26	0.24	313	0.237
150	0.25		367	0.238

The effect of magnetic fields on the thermal conductivity of zinc was investigated by H. M. Brown.²² He found that a longitudinal field of 10,000 gauss produced no change in the thermal conductivity of zinc at 0°C. which was reported as 0.280 cal. per sq. cm. per cm. per second per °C.

Heat of Combustion—C. G. Maier²³ reviewed the status of investigations on the heat of formation of zinc oxide and reported new experimental work that indicated definitive values. For dry oxide and wet oxide the values were ΔH_{ox} = -83156 and -83200, respectively. The free energy of formation of the oxide from cell measurements was shown to be $\Delta^{\circ}F_{\text{ox}}$ = -75930 and the value calculated from entropies was -75979. The agreement was thought to be well within the estimated probable error of the calorimetric work on zinc oxide (about 50 calories).

Optical Properties—The reflection of light rays from zinc is, of course, a function of the condition of the surface of the specimen. Provostaye and Desains²⁴ state that 68% of normally incident white light is reflected by zinc. Drude²⁵ found that 77% of red light is reflected. In neither case is the condition of the surface specified.

The Smithsonian Physical Tables state that the total radiation from an oxidized zinc surface is 0.110 as compared with a black body at 1.00.

Burkhardt²⁶ quotes the following data from Coblenz²⁷ on the relationship of reflection and wave length:

Wave length in microns.....	188	200	251	305	357
Reflection in %.....	17	22	39	48	51

Coblenz²⁷ also found that the reflectivity of a polished zinc surface goes through a minimum at 1 micron, rising immediately and reaching a peak value beyond 2 microns.

Electrical Properties—A number of investigators have reported data on the electrical resistivity of zinc single crystals. The following table gives some characteristic data.

Investigator	Type of Zinc Used	Temperature, °C.	Electrical Resistivity (Ohms per cm. ³)	
			Parallel to Hexagonal Axis	Perpendicular to Hexagonal Axis
Tyndall and Hoyem ²⁸	S.P.	20	6.16×10^{-6}	5.83×10^{-6}
Tyndall and Hoyem ²⁸	Kahlbaum's Best	20	6.20×10^{-6}	5.86×10^{-6}
Bridgman ²⁹	Kahlbaum's Best	20	6.06×10^{-6}	5.83×10^{-6}
Way ³⁰	99.99+	20	6.170×10^{-6}	5.842×10^{-6}
Poppy ³¹	99.99+	20	6.161×10^{-6}	5.842×10^{-6}

The Bureau of Standards,³² working with polycrystalline spectrographically pure zinc wire swaged to 0.07 in. dia., obtained a value of 5.916×10^{-6} ohms per cm.³ at 20°C.

The temperature coefficient of resistivity of a single crystal of spectrographically pure zinc was determined by Hoyem³³ as 4.058×10^{-4} . This is an average value for a temperature range of -170°C.-25°C. and includes measurements made at angles from 1°-86.5° to the hexagonal axis. Spectrographically pure zinc wire, swaged to 0.07 in. dia. and drawn to 0.0089 in., was found by the Bureau of Standards³² to have a temperature coefficient of resistivity of 4.19×10^{-4} in the range 0°-100°C.

The electrical conductivity of rolled zinc varies with the composition and rolling treatment. Determinations made at 20°C. by The New Jersey Zinc Co.³ on specimens cut parallel to the rolling direction are given below:

Type of Zinc	Treatment	Electrical Conductivity	
		Mhos $\times 10^4$	Relative (Cu = 100)
99.94% pure	Hot rolled	18.50	28.44
99.94% pure	Cold rolled	18.40	28.27
1.1% Pb, 0.05% Cd	Hot rolled	18.34	28.17
1.1% Pb, 0.05% Cd	Cold rolled	18.28	28.06

Electrochemical Equivalent—The 1933 Smithsonian Tables give the electrochemical equivalent as 1.21950 g. per ampere hour.

Electrolytic Solution Potential—The single electrode potential of zinc in a solution of normal metal ion concentration is given as -0.7581 by Lewis and Randall^{4a} and as -0.76 by Blum and Hogaboom.^{4b} These values are based on the normal hydrogen electrode as zero and are calculated from measurements made on dilute solutions in which the metal ion concentrations are measured.

Thermoelectromotive Force—The Bureau of Standards¹⁰ have determined the thermal emf. of spectroscopically pure zinc against pure No. 27 platinum wire. The spectroscopically pure zinc was swaged to 0.07 in. dia. and then cold drawn to 0.0365 in. The cold junction was at 0°C. and the emf. given below is that developed at the temperature of the hot junction.

Temperature, °C.	Emf. (Millivolts)	Temperature, °C.	Emf. (Millivolts)
0	0.000	250	2.610
50	0.331	300	3.417
100	0.758	350	4.310
150	1.276	400	5.290
200	1.894	415	5.604

Magnetic Susceptibility—McLennan, Ruedy, and Cohen⁴ give the following data on the magnetic susceptibility of zinc single crystals: Parallel to hexagonal axis = -1.90×10^{-7} ; perpendicular to hexagonal axis = -1.45×10^{-7} .

Work in the authors' laboratory⁸ on polycrystalline specimens, 99.94% pure, shows that in the as cast condition the magnetic susceptibility is about -8.36×10^{-7} while annealing at 375°C. for 20 hr. raises this value to about -1.2×10^{-6} .

Supra Conductivity—The resistance of zinc vanishes at 0.79° absolute, according to the work of W. G. Keesom⁴ as summarized in Chemical Abstracts. The zinc used was high purity metal obtained from the Bureau of Standards. While not stated in the Abstract, it is probable that the zinc was of 99.993% purity and was tested in the cast form.

Transmission of Sound—The velocity of sound in zinc has been determined by Masson⁴ as 3,700 meters per sec. (16,140 ft. per sec.). The velocity of sound in air is 332 meters per sec. While no specific statement is made, the above data probably refer to cast zinc at room temperature.

Surface Tension—The Bureau of Standards¹⁰ have tabulated the following values from various sources:

Temperature, °C.	Capillary Constant ^a A ² — mm. ³	Surface Tension Dynes per cm.	Sources
450	...	755 ^b	Hogness
477	23.5	753	Hogness
500	...	751 ^b	Hogness
543	23.6	747	Hogness
590	24.54	707.5 ^c	Smith
600	24.99	787 ^d	Bircumshaw
700	24.63	763	Bircumshaw

^aA² = radius of capillary tube \times height.

^bCalculated by means of equation $r = 758 - 0.090(t-419)$

^cMean value 580-630°C.

^dZinc used contained 0.035 Cd, 0.008 Fe, 0.006 Pb, trace Cu.

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Properties of Wrought Zinc and Zinc Alloys

By E. H. Kelton*

General—Wrought zinc and zinc alloys may be obtained in the form of rolled strip and sheet and drawn rod and wire. Wrought zinc has desirable corrosion resistant properties for many types of service, and as corrosion products that may form are colorless, they do not stain other materials. Wrought zinc has chemical characteristics particularly adapted to certain uses such as dry batteries and offers combinations of desirable physical and mechanical properties at relatively low cost. Practically all commercial wrought zinc contains small amounts of natural impurities, mainly lead, iron, and cadmium (see the article on "Zinc Industry", Table I), while the present commercial alloys usually contain additions of copper up to about 1% and sometimes smaller amounts of other elements.

Rolled Zinc—By far the commonest forms of wrought zinc are rolled strip and sheet. Rolled zinc may be fabricated by drawing, forming, stamping, bending, or spinning. Practically all of the companies which market rolled zinc produce a grade which approaches "Intermediate" in analysis and one or more others of higher or lower purity. The classifications used in Table I are arbitrary. The analyses shown are typical ones covering the range and do not necessarily include every variation found among the grades produced by the various companies. Each grade listed is representative of one of what may be termed the standard types produced by practically all zinc rollers. In addition, many producers market special grades which are intermediate to those listed and usually produced to meet a special class of business.

Drawn Rod and Wire—Zinc and zinc alloy rod and wire are produced from rolled or extruded rods afterwards drawn to the desired sizes in much the same manner as brass. There is no wide use for zinc in this form at present but comparatively small quantities are produced for use in spray metal coating, and, in small sizes, for weaving into brake linings.

Mechanical Properties—In the testing of zinc and zinc alloys, it is essential to control closely the testing temperature and speed. The values listed in Table II were obtained at tensile speeds of $\frac{1}{4}$ in. per min. head speed on 2 in. gage lengths at a temperature of 70-80°F.

The tensile strength values shown in Table II may be used in calculating the effect of intermittent loads. Due to the fact that creep is encountered in zinc at room temperature at loads well below the ultimate strength, entirely different data must be used in dealing with continuous loads. In general, the purer the zinc and the higher the service temperature, the lower the resistance to creep. Suppliers should be consulted for data applicable to particular problems where continuous loads are involved. For instance, 10,000 psi. is the figure usually used as the static strength of a zinc alloy used for roofing and rolled especially for highest static tensile strength. Designing on this basis rather than using a tensile strength of, say 35,000 psi., insures against unsightly sagging of the sheets under static roofing loads.

No true elastic limit can be determined by ordinary methods because of the creep phenomenon. The necessity for controlling the speed and temperature of testing is due to the same cause.

Fabrication of Rolled Zinc and Zinc Alloys—All severe fabricating operations should be carried out at temperatures above 70°F. Warm soapy water (using a neutral soap to avoid staining) is the cheapest lubricant available and is as satisfactory as any.

Rolled zinc and zinc alloys of the proper grades are readily drawn into a great variety of articles such as battery cups, eyelets, meter cases, vanity cases, flashlight reflectors, and fruit jar caps. They are just as readily rolled or press formed, stamped, or spun into a wide variety of items such as addressing machine plates, buckles, ferrules, cans, cases, ornaments, name plates, gaskets, weatherstripping, or lamps.

Deep Drawing—In the deep drawing of rolled zinc and zinc alloys the following points should be observed:

The reduction in diameter from blank to first cup should not exceed 40%. The

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Table I
Classification of Wrought Zinc

Grades	Pb	Fe, Max.	Composition, %			Zn	Characteristics	Suggested Uses
			Cd	Cu	Mg			
a	0.05 max.	0.010	0.005 max.	0.001 max.		Balance	Provides max. softness and ductility. Self annealing at room temp.	Spinning trade.
b	0.05-0.12	0.012	0.005 max.	0.001 max.		Balance	High ductility with low stiffness. Uniform corrosion characteristics in dry cells. Susceptible to almost no work hardening.	Battery cans, fuses, drawn and formed articles.
c	0.30-0.65	0.020	0.20-0.35	0.005 max.		Balance	Stiffness and good ductility. Uniform corrosion characteristics in dry cells. Uniform etching qualities. Capable of some work hardening.	Battery cans, photoengravers' sheet, boiler and ship plates, weatherstrip.
d	0.05-0.12	0.012	0.005 max.	0.65-1.25		Balance	High stiffness and hardness. Good ductility. Better creep resistance than Grade C. Can be work hardened.	Weatherstrip, grommets, drawn and formed articles requiring stiffness.
e	0.05-0.12	0.015	0.005 max.	0.75-1.25	0.007-0.02	Balance	Max. hardness, stiffness, and creep resistance. Excellent work hardening properties. Requires special fabricating technique.	Corrugated roofing, articles requiring max. stiffness.

reduction in diameter of succeeding cups should not exceed 20% unless holding sleeves on the draw punches, or their equivalents are used.

In general, radical clearance between the punch and die on the first draw should equal the thickness of the stock. On succeeding draws the clearance should be cut down to pinch the metal slightly.

The softer grades of rolled zinc are self annealing at the temperatures developed during drawing, and hence no annealing is required between operations. The harder grades work harden somewhat and may require annealing if there are a large number of redrawing operations. Annealing at temperatures slightly above 212°F. is usually sufficient.

Table II
Mechanical Properties of Wrought Zinc and Zinc Alloys

Composition, %	Rolling Treatment	Scleroscope Hardness	With Grain ¹	
			Ultimate Tensile Strength, Psi	Elongation in 2 In., %
Pb 0.05 max.	All	13-15	16,000-19,000	40-70
Fe 0.010 max.				
Cd 0.005 max.				
Pb 0.12 max.	Hot Cold	14-15 15-18	17,000-20,000 18,000-23,000	40-70 30-60
Fe 0.012 max.				
Cd 0.005 max.				
Pb 0.15-1.0	Hot Cold	15-17 17-21	19,000-23,000 20,000-26,000	30-60 30-60
Fe 0.020 max.				
Cd 0.10-0.35				
Pb 0-1.0	Hot Cold	15-22 18-30	21,000-40,000 26,000-50,000	20-60 20-60
Fe 0.020 max.				
Cd 0-0.35				
Cu 0.65-1.25	Annealed 250°C.	14-18	18,000-30,000	20-50
Mg 0-0.025				

¹Across grain tensile values average roughly 20% higher than the with grain values in strip rolled metal. The elongations are correspondingly lower.

The properties in Table II are the average limiting values to be secured by ordinary sheet or strip rolling methods. The wide ranges of values are secured by varying the analysis of the metal, the rolling treatments and, except in the case of the hardness, the direction of testing.

Some of the rolled zinc alloys have very marked work hardening characteristics and require annealing at temperatures of 400-500°F. to carry out a series of redrawing operations successfully. For instance, a certain article may require a cupping operation followed by four redrawing operations. If the cupping operation involves a 42% take-in and the redraws 15-20% take-ins, the cups may start to split at the tops on the third redraw. It is usually more economical to anneal the second redraw cups than to redesign the tools to lighter take-ins and add another redrawing operation. In this annealing, it is only necessary to bring the cups to the required temperature, but it is customary to leave them in the furnace for several hours to insure that all of the cups reach the desired temperature. It may be necessary to exert some care to prevent extremely coarse recrystallization and consequent weakening of the sections of the cup which have not been severely worked. These details must be worked out separately for each article and each alloy, but coarse crystal growth can generally be prevented by utilizing the lowest practicable annealing temperature and spreading out the cups so that the shortest possible annealing time can be employed.

Soldering—Rolled zinc and zinc alloys are easily soldered by conventional methods. The usual precautions regarding proper cleaning and fluxing should be observed. To prevent overheating and consequent loss of physical properties the soldering should be done as rapidly as possible.

Machining—Observe the same principles for machining as set forth in the article on "Zinc Die Castings".

Plating, Painting, Lacquering and Enameling—In general, the same methods are used in the finishing of wrought zinc and zinc alloys as are used in finishing zinc base die castings. See the article on "Zinc Die Castings". However, greater caution should be exercised in baked enameling not to exceed temperatures which will impair the mechanical properties. For this reason, air dried finishes are preferable.

Marking—Zinc may be easily marked by the use of commercially prepared metal inks. Such markings are waterproof.

Polishing of Zinc and Its Alloys for Metallographic Examination

By E. A. Anderson* and J. L. Roddat

The preparation of zinc for metallographic examination requires care, not only by reason of the relative softness of the pure metal but because slight distortion will readily cause the formation of mechanical twins. In fact, the presence or absence of twinning may frequently be used as a measure of the care used in preparing the microspecimen. The susceptibility to distortion or mechanical twinning naturally decreases as the hardness of the zinc is increased by alloying or refinement of grain size.

Not infrequently instructions for preparing microsections will be found in which it is directed to continue polishing until scratches from the preceding operation have been removed, although many metallurgists have recognized that this is not sufficient. Experiment has shown¹ that during the normal polishing of cast zinc, distortion may occur to a depth of from 20-100 times as great as the deepest scratch. Since the time required to produce an ideal surface by polishing alone, particularly during the final stages, would be excessive, a saving can be made by etching away some of the metal between polishing steps. This method obviously cannot be used on specimens having relatively large areas of phases having different etching characteristics, since a strong relief once developed cannot be removed on a yielding cloth lap.

Preparation of the surface can be divided into three stages: (1) Rough grinding, preferably on a belt sanding machine; (2) fine grinding by hand on abrasive papers, and (3) polishing on rotating cloth covered discs

For grinding on the sander the following four grades of belts have been found satisfactory: "No-lap" No. 30, 60, 120, and 240. Undue heating of the specimen must be avoided since commercial grades of unalloyed zinc recrystallize at temperatures easily attained at the surface during grinding. Preliminary surfacing on the sander must be carried far enough that distortion from a previous cutting or sawing operation is removed. At least $\frac{1}{16}$ in. should be removed for this purpose.

Hand polishing may be satisfactorily carried out with a series of three or four polishing papers such as "Speed-wet" No. 280, 320, and 400 or Behr-Manning No. 1, 0, 00, and 000. The paper should be backed by a flat surface such as plate glass.

For wet polishing, the use of specially graded abrasives is highly desirable. Methods of preparation and use have been described.¹ Briefly, the method consists of dispersing the commercial abrasive (alumina) in water with a peptizing agent** in a ball mill, then transferring to a beaker. Portions of the supernatant suspension are drawn off at stated intervals so that particles in suspensions for the respective wheels have the following maximum settling rates: No. 1 wheel—1 in. in 20 sec.; No. 2 wheel—1 in. in 3 min.; No. 3 wheel—1 in. in 30 min.; and No. 4 wheel—1 in. in 4 hr. The settling rates from one wheel to the next thus decrease in the approximate ratio of 9-1 while the particle diameter decreases in about the ratio 3-1.

The first two polishing wheels may be covered with white duck. Either a good grade of broadcloth or billiard cloth is suitable for the last two wheels. Finishing on billiard cloth is preferable. The operator's hands and the specimen should be washed with soap and water between operations to avoid the introduction of coarser grit to any wheel.

Using a solution containing 200 g. pure chromic anhydride (CrO_3), 15 g. sodium sulphate (anhydrous), or 34 g. $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, 1000 cc. water, the following etching schedule has been found satisfactory for removing most of the metal distorted by polishing. As previously noted, this procedure cannot be used where large particles are present of another phase having different etching characteristics.

Etch $3\frac{1}{2}$ minutes after final hand polishing
1½ minutes after No. 1 wheel
30 seconds after No. 2 wheel
10 seconds after No. 3 wheel

After polishing on the fourth wheel the specimen may be etched for microscopic examination. (The etching procedure is described in the following article.)

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**An agent called "Darvan", used in the rubber trade, has been found better than the sodium silicate first used. Other satisfactory agents are doubtless available.

Mounting Specimens—A brief description of mounting methods may be useful. Rolled metal is commonly polished on a with-grain edge section and may be conveniently mounted in a screw clamp with thin spacers of soft zinc between specimens and heavy strips of zinc outside the assembly. The assembly is tightly clamped to prevent seepage of etching reagents between specimens. The zinc spacers, whose structure is known, serve as a convenient standard of comparison to determine whether or not preparation of the specimens has been properly carried out.

Some of the synthetic resins such as Lucite or Bakelite are convenient mounting media¹ for brittle or irregularly shaped specimens, particularly when microexamination to the very edge is required. With these transparent media, the shape of the specimen can be observed and surface features correlated with microstructure. For many purposes the mounting temperature and time are such that no marked structural changes occur. Convenient presses for the purpose are available on the market.

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Etching of Zinc and Zinc Alloys for Metallographic Examination

By E. A. Anderson* and J. L. Rodda†

The most useful etching reagent for zinc is a solution of pure chromic anhydride, CrO_3 (commonly called chromic acid) to which pure sodium sulphate has been added.¹ A pure chromic anhydride solution will not etch zinc. Sulphates and certain other ions appear to act as catalysts, permitting the zinc to be dissolved and the hexavalent chromium reduced. Accurate control of the relative proportions and absolute amounts of chromic anhydride and sulphate is essential to the production of dependable structures and etching rates. Since commercial grades of chromic anhydride frequently contain sulphate as an impurity, it is essential that pure chemicals be used. A grade of chromic acid used for plating has been found satisfactory. Chromic anhydride may be readily tested for the presence of sulphate or other catalyzing ions since a solution of the pure chemical will not etch zinc.

Final polishing of the specimen is best done just before etching. The tip of the finger dipped in alcohol and rubbed over the surface of the specimen will remove any loose abrasive. The specimen should be cleaned by dipping successively in alcohol, ether, alcohol, then in a strong stream of water, excess water shaken off and the specimen etched.

The most useful etching composition for commercial grades of zinc is as follows:

Solution No. 1	Solution No. 2
200 g. pure CrO_3 15 g. Na_2SO_4 or 34 g. $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ 1000 cc. water	200 g. pure CrO_3 1000 cc water

Fifteen seconds immersion will be adequate for examination at 100 dia. At 1000 dia etching for periods longer than one second will frequently cause too much relief.

Certain chromic anhydride-sulphate mixtures, some of which may be produced by diluting the reagent with water, produce a stain film on zinc. This film is soluble in a pure CrO_3 solution which itself will not etch or stain. Use of solution No. 1 or others containing chromic anhydride should therefore be followed immediately by rinsing in solution No. 2. This rinse is followed by thorough washing in a strong stream of water, dipping in alcohol, then ether and drying with a warm blast of clean air.

Etching Copper-Zinc Alloys—For zinc containing copper in solid solution a reduction in the sulphate content of solution No. 1 produces better contrast:

Solution No. 3
200 g. CrO_3 7.5 g. Na_2SO_4 1000 cc. water

Electrolytic etching² in a solution of 200 g. CrO_3 and 1000 cc. water has been found useful in studying other copper-zinc phases, particularly gamma and epsilon. The etching results depend somewhat upon the grain size and distribution of the phases and some experience is required in interpreting the results. In general, however, at current densities greater than 1.5 amperes per sq. in. gamma will be attacked in preference to epsilon; at lower current densities epsilon will be attacked in preference to gamma. Platinum foil or wire may serve as cathode and the current should be on when the specimen is dipped into the solution. Five seconds etching is usually adequate at the higher current densities.

Die Casting Alloys—Structures developed on die casting alloys by solution No. 1 are somewhat unsatisfactory in that the aluminum-rich phase (gamma) is not attacked. G. Edmunds and O. W. Bartholomew³ have found that, in the presence of sodium fluoride, a chromic anhydride solution will etch gamma. By a combination

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of the sulphate and fluoride catalysts the desired result is obtained. The recommended concentrations are:

Solution No. 4
200 g. CrO_3
7 g. Na_2SO_4
2 g. NaF
1000 cc. water

Some slight staining results with alloys containing copper. This may be prevented by transferring the specimen, without washing, to a solution of:

Solution No. 5
50 g. CrO_3
4 g. Na_2SO_4
1000 cc. water

Since this also is an active etching reagent immersion should be brief. Two seconds in No. 4 and one second in No. 5 is usually satisfactory for photographing at 1000X. This treatment should be followed by the usual rinse in solution No. 2 before washing and drying.

Macroetching—Concentrated hydrochloric acid produces good grain contrast on zinc.

References

¹O. H. Mathewson, C. S. Trewin, and W. H. Finkeldey, Some Properties and Applications of Rolled Zinc Strip and Drawn Zinc Rod, Trans. A.I.M.E., 1920, v. 64, p. 305.

²J. L. Rodda, Notes on Etching and Microscopical Identification of the Phases Present in the Copper-Zinc System, Trans. A.I.M.E., 1937, v. 124, p. 189.

³Unpublished data, The New Jersey Zinc Co., Palmerton, Pa.

Manufacture and Properties of Zinc Die Castings

By E. A. Anderson¹ and Marc Stern²

The Die Casting Process—The die casting process may be defined as the method of making reproducible shapes by casting in a metal die or mold with pressures exceeding those due to gravity. The die casting machine consists of a pot in which to melt the alloy and hold it at the desired casting temperature and a means of forcing the molten metal under high pressure into a die held in a suitable frame which permits it to be opened and closed at will. By suitable use of retractable cores a wide range of shapes may be produced by this method.

Applications—Die castings offer certain distinct economies. Where a number of parts of the same design are required, the use of die castings permits large reductions in machining costs. Parts of intricate ornamental design may be produced at low cost. Several parts may be combined in one die cast, thus reducing assembly costs. When desired, the die castings may be plated, chemically treated, lacquered, enameled, painted, or coated with other organic finishes.

Of the various metals suitable for pressure die castings, zinc has the advantage of low material cost. Furthermore, because of the low melting point of zinc alloys, good die life may be obtained with dies of plain carbon steel and it is not necessary to give the dies special heat treatment.

The following established uses give a general idea of the wide range of suitable applications. In the automotive field body hardware, carburetors, fuel pumps, radiator ornaments, speedometer frames and taxi meter housings and parts are commonly die cast from zinc alloys. Gears for many uses including washing machine and electric hoist gears have proven successful. Refrigerator hardware, door checks, and other interior hardware in the building field; small motor frames, radio chassis and parts in the electrical industry and various housings and brackets, in business equipment offer further examples.

Design—The limitation of size has not been reached. Typewriter frames and radio chassis are fair examples of large castings. The die cast cowl bar weighing 14 lb., with an over-all length of 41 in. and die cast radiator grilles weighing 20-30 lb. represent even larger parts which have come into use. Parts such as the individual units in die cast slide fasteners represent a large field of very small die castings.

The accuracy of dimensions ordinarily attained is ± 0.002 in. per in. of length or fraction thereof up to 3 in. and ± 0.001 in. per in. for each additional inch. Dimensions intercepted by the parting line of the die will show a greater variation, but proper die design will usually avoid having the parting line intercept important dimensions. A draft of 0.001 in. per in. on cores is the minimum desirable allowance.

Alloys—While a number of zinc alloys have been employed in the past, modern die casting practice recognizes only three alloys, all of which have been covered by S.A.E. specifications* and are included in A.S.T.M. specification B86-38T. The compositional limits for these three alloys are given under their specification designations in Table I.

Table I
Composition of Zinc Die Casting Alloys

	S.A.E. No. 903 A.S.T.M. No. XXIII	S.A.E. No. 921 A.S.T.M. No. XXI	S.A.E. No. 925 A.S.T.M. No. XXV
Copper	0.10 Max.	2.5-2.5	0.75-1.25
Aluminum	3.5-4.3	3.5-4.5	3.5-4.3
Magnesium	0.03-0.08	0.02-0.10	0.02-0.08
Iron—Max.	0.100	0.100	0.100
Lead—Max.	0.007	0.007	0.007
Cadmium—Max.	0.005	0.005	0.005
Tin—Max.	0.005	0.005	0.002
Zinc	Remainder	Remainder	Remainder

Note: A.S.T.M. Alloy No. XXIII, S.A.E. No. 903, is covered by U. S. Patent No. 1,779,525. A.S.T.M. Alloy No. XXI, S.A.E. No. 921, is covered by U. S. Patent No. 1,596,761. A.S.T.M. Alloy No. XXV, S.A.E. Alloy No. 925 is covered by U. S. Patent No. 1,852,441.

Properties—The physical and mechanical properties of these alloys are given in Table II.

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*S.A.E. Handbook, 1937 Edition, pages 424-426.

Table II
Physical and Mechanical Properties of Zinc Die Casting Alloys

	A.S.T.M. No. XXIII, S.A.E. No. 903	A.S.T.M. No. XXI, S.A.E. No. 921	A.S.T.M. No. XXV S.A.E. No. 925
Tensile strength, psi.....	40,300	47,900	44,500
Impact strength, ft.-lb. ^a	20	19	17
Elongation, % in 2 in.....	4.7	5.1	3.0
Transverse deflection, in.....	0.27	0.22	0.16
Modulus of rupture, psi.....	95,000	116,000	105,000
Compressive strength, psi.....	60,500	93,100	87,300
Shearing strength, psi.....	30,900	45,800	38,400
Electrical resistivity, ohms per cm. ³ at 77°F.....	0.000064	0.000089	0.000087
Electrical conductivity, mhos per cm. ⁴ at 77°F.....	155,000	144,000	150,000
Thermal conductivity, calories per sec./cm. ² /°C. (25-100° C.)..	0.27	0.25	0.26
Thermal expansion/unit length/°C.....	0.0000274	0.0000277	0.0000274
Thermal expansion/unit length/°F.....	0.0000152	0.0000154	0.0000152
Specific gravity.....	6.8	6.7	6.7
Specific heat cal./g./°C.....	0.10	0.10	0.10
Melting point, °F.....	717.6	715.1	717.1
Solidification shrinkage, in. per ft.....	0.14	0.15	0.14
Brinell hardness ^b	60-90	75-100	70-85

^aOn unnotched $\frac{1}{4} \times \frac{1}{4}$ in. sq. bar, Charpy test.

^bBrinell or Rockwell hardness tests on die castings are generally considered unreliable.

Note: Properties given above are average figures for alloys as die cast. For information on lower limit of properties to be expected in commercial castings, see A.S.T.M. Specification B86-38T.

While the above alloys compare fairly closely in composition, the variations in copper content induce differences in properties which should be taken into consideration in selecting an alloy for a given application. General information concerning these differences is given below.

A.S.T.M. Alloy No. XXIII (S.A.E. No. 903)—This alloy is the most permanent with regard to dimensions and ductility of the commercially used alloys. Its impact strength should not change appreciably under any ordinary service conditions. No dimensional change exceeding 0.001 in. per in. is to be expected in castings of this alloy under normal service conditions. The extent of this dimensional change can be materially reduced by an inexpensive heat treatment.

A.S.T.M. Alloy No. XXI (S.A.E. No. 921)—This alloy has the highest tensile strength and hardness of the commercial zinc alloys. It is inferior to S.A.E. alloys No. 903 and 925 in permanence of dimensions and retention of impact strength at room and elevated temperatures.

A.S.T.M. Alloy No. XXV (S.A.E. No. 925)—This alloy is intermediate between Alloys No. 903 and 921 in tensile strength and hardness. At room temperature, it is equal to Alloy No. 903 in permanence of dimensions and impact strength. At elevated temperatures, it is subject to growth in dimensions and loss in impact strength of lesser magnitude and slower rate than Alloy No. 921. It is somewhat more resistant to surface corrosion than Alloy No. 903. It may be used in virtually any application to which Alloy No. 921 is suited and in place of Alloy No. 903 when additional surface corrosion resistance is required in addition to better permanence than can be obtained with Alloy No. 921.

Steam Test—An exposure in an atmosphere saturated with water vapor at 95°C. for a period of ten days is accepted by the A.S.T.M. as a check on the freedom of the alloy from excessive contents of lead, cadmium, and tin. No undesirable corrosion will take place in this test if the alloys are made to the compositional limits given in Table I.

General—It is generally believed that the physical properties of a cast metal are dependent in a large degree on the casting conditions and the design of the castings. This is particularly true in die castings where there is opportunity for a wide variation in metal flow and chill due to the design, cooling, and operating temperature of the die. The zinc alloys mentioned above are affected by such conditions. For example, the tensile strength may be increased by unusual chilling or lowered through casting in an unusually hot die. The impact strength usually tends to increase with increasing die temperature up to some maximum fixed by the die design, after which a reduction in impact strength may take place with further increases in die temperature.

Die castings are usually of such size and shape that test specimens cannot be machined for actual die cast parts. A standard die for casting tensile and

impact specimens has, therefore, been recommended by Committee B-6 of the A.S.T.M. and widely adopted. The tensile specimen is round with a $\frac{1}{4}$ in. reduced section. The standard unnotched $\frac{1}{4}$ by $\frac{1}{4}$ in. impact specimen is used.

The data on physical properties given in Table II are based on specimens cast in such dies under average conditions. It must be recognized that various sections of commercial castings may differ considerably in properties from these figures due to differences in chill and metal flow.

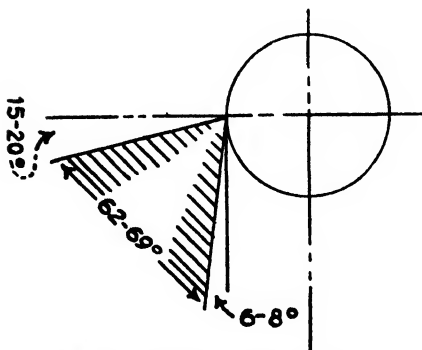


Fig. 1—Cutting angles for zinc.

Machining—A primary machining requirement is the maintenance of a keen, smooth cutting edge. High speed steels are usually satisfactory, but for exacting dimensional requirements special cutting tools, such as tungsten carbide, are effective. Cutting angles for machining zinc are given in Fig. 1.

Milling cutters, end mills, reamers, and similar tools produce the best results when they are of coarse tooth spiral or helical design with appreciable top and side rake. Two-fluted spiral taps with ground and relieved threads which provide ample chip clearance and rapid chip removal have been found satisfactory.

The same principle applies to drills where two-fluted drills, with spiral angles about double the usual 24° , are satisfactory.

The included angle of the cutting edges may be advantageously reduced. The clearance angle may be increased to 15° at the periphery of the drill and gradually increased still further as the drill point is approached. Beveling off the end of the flute back of each cutting edge provides more chip clearance for rapid work.

Finishing—Electroplated finishes are largely employed in finishing zinc base die castings. The degree of protection against various exposure conditions which can be obtained by plating is dependent in the case of zinc die castings as in the case of other metals upon the quality and weight of plating. In present practice, coatings in the order of 0.001 in. in thickness are considered necessary for satisfactory protection under conditions of outdoor exposure.

While nickel is widely used as the first coat under chromium finish coatings, it is impossible to safely produce heavy coatings with a single deposit of nickel. Any warm nickel solution which contains no sodium sulphate and operates above pH 4.8 may be used in producing heavy deposits on zinc, provided a protective strike coating is first applied. This strike coating may be either copper or nickel. For copper plating a cyanide solution containing Rochelle salt is widely used. A solution suitable for nickel strike plating is as follows:

Single nickel salts—10 oz. per gal. (75 g. per l.)
 Anhydrous sodium sulphate*—15 oz. per gal. (112 g. per l.)
 Ammonium chloride—2 oz. per gal. (15 g. per l.)
 Boric acid—2 oz. per gal. (15 g. per l.)
 Temperature—Room temperature.
 Current density—8 to 20 amperes per sq. ft.

After strike plating for 5 min. in the above solution, the work is rinsed in cold water and transferred to a warm nickel solution for completion of the plating. Work which has received a copper strike is rinsed thoroughly, dipped briefly in a 5-20% sulphuric acid solution, again rinsed, and placed in the warm nickel solution.

The preparation of the castings for plating does not present any unusual problems. It is best to avoid deep grinding which may cut through the surface layer which offers the best surface for plating. Any suitable proprietary cleaner may be used. The following solution used as an electrocleaner at $170-180^\circ\text{C}$. has operated successfully:

6 oz. of trisodium phosphate per gal. of water (45 g. per liter).

Care should be taken to avoid overcleaning and the work should be given a brief dip in 5% hydrochloric or 5% sulphuric acid to neutralize alkaline films before plating.

*Use 20 oz. per gal. if hydrous sodium sulphate is used.

Organic finishes will normally require chemical pretreatment to insure satisfactory adherence. Of those tested, the phosphate type of pretreatment appears to be the most effective. Lacquers may be used effectively but better adherence qualities are obtainable with baking finishes. Baking finishes are available which may be applied at baking temperatures as low as 250°F. The use of higher temperatures is possible under some conditions, although the possible effect of the temperature on the physical properties should be taken into consideration. With excessive temperatures, there is danger of blisters forming as the result of the expansion of any air bubbles near the surface of the casting.

GENERAL INDEX

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